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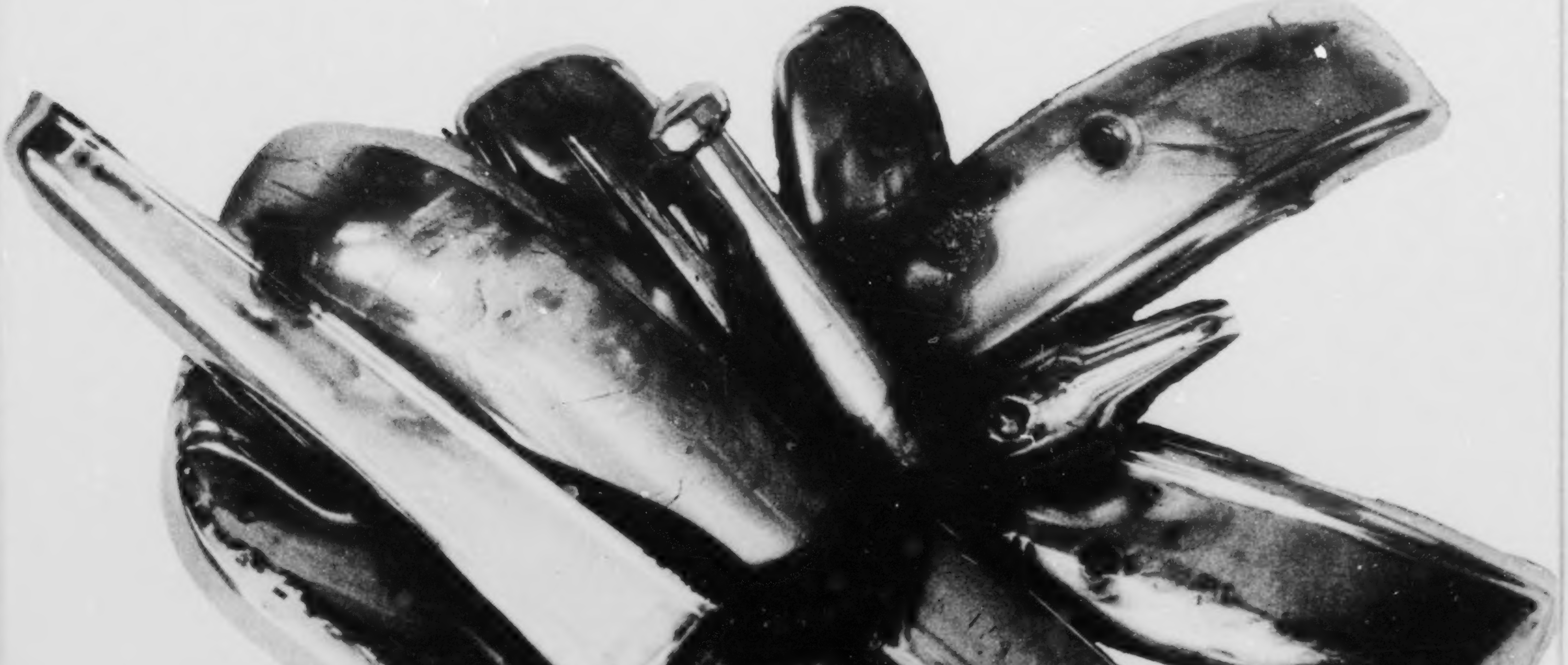
RECOVERY AND UTILIZATION OF MUNICIPAL SOLID WASTE



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This report compiles available cost and performance characteristics of processes that are, or might be, employed in solid waste recovery and utilization. The information was obtained from operators of existing systems, equipment manufacturers, and selected experts and the study is focused on size reduction, separation, and recovery and utilization. Among the conclusions, it was found that more than two-thirds of size reduction equipment is used primarily on uniform material in industry and is not recommended for direct use on municipal solid waste; with the exception of magnetic separation, the degree to which the separation techniques studied can be adopted in practice is not well established because of the lack of suitable cost and performance data upon which to base evaluations; in the area of recovery and utilization of mixed solid waste, byproduct recovery appears to have greater economic potential than does material salvage. Solid waste recovery may never become economic in the engineering sense; the external diseconomics and social costs associated with the disposal-oriented methods of solid waste management may, however, provide a strong motivation for development of recovery techniques.

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RECOVERY AND UTILIZATION OF MUNICIPAL SOLID WASTE

A summary of available cost and performance characteristics of unit processes and systems

This report (SW-10c) was prepared for the Solid Waste Management Office
by N. L. DROBNY, H. E. HULL, and R. F. TESTIN
Battelle Memorial Institute, Columbus Laboratories
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Foreword

AS DIRECTED BY CONGRESS,[1] the emphasis of the national solid waste management research program should be shifted from *disposal* toward *recycling and reuse*. This is perhaps part of a recent national turning from over-affluence and conspicuous consumption towards values encompassing a quality environment. Resource recovery would be part of a national return to the prudent Yankee temperament. And none too soon.

According to the feedback now coming from all parts of our ecosystem, the self-regulating controls of nature's economy are signaling that the system is dangerously overloaded and may become inoperative. Thus, traditional Yankee prudence combined with soaring American imagination, are very much needed in solving the Nation's ecologic crisis. This document, which continues the work begun by our survey of the state of the art of solid waste processing,[2] can contribute its specifics to that national effort.

—RICHARD D. VAUGHAN
Assistant Surgeon General
Acting Commissioner
Solid Waste Management Office

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[1] The Solid Waste Disposal Act. Sec. 202, Title II of Public Law 89-272, 89th Cong. S.306, October 20, 1965, as amended, 91st Cong., 1970.

[2] Engdahl, R. B. Solid waste processing; a state-of-the-art report on unit operations and processes. Public Health Service Publication No. 1856. Washington, U.S. Government Printing Office, 1969. 72 p.

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I. Summary

Solid waste constitutes a resource disguised as a nuisance. This is the underlying philosophy that has motivated this study. The study has resulted in this sourcebook of all available cost and performance characteristics of unit processes that are, or might be, employed in solid waste recovery and utilization. The study covers three main areas: size reduction, separation, and recovery. Recovery includes both direct salvage and the manufacture of new byproducts.

The cost and performance information presented herein provides a basis for preliminary technical and economic evaluations of equipment and processes for recovery and utilization of solid waste. The primary information sources for the study were the operators of existing processing systems, equipment manufacturers, and selected experts. Over 200 such contacts were established. A previous study conducted by Battelle had indicated that the information needed could not be found in the published literature.[1] Because existing applications of equipment and processes to the recovery and utilization of solid waste are not well documented in quantitative terms, potential uses of industrial processes were also investigated. Examples include the minerals beneficiation, pulp and paper, and chemical processing industries. Primary problems encountered in the study were the lack of existing operational data, questionable reliability of available data, and proprietary constraints that made it impossible to obtain some data. Where warranted, engineering estimates were employed to fill data gaps.

It is essential for the separation and eventual recovery of solid waste that the components to be processed be physically free from one another. This, in turn, often implies a need for size reduction to precede salvage or by-product manufacture.

Size-reduction equipment employs three basic forces—compression, tension, and shear—in various combinations. Available cost and performance data were collected for nine types of equipment which differ principally in their application of the above three forces; these are crushers, cage disintegrators, shears, shredders, rasp mills, drum pulverizers, disk mills, wet pulpers, and hammermills. Based upon data obtained from the various sources, relationships were generated indicating power requirements and product cost as a function of throughput. Estimates were developed for product cost and power requirements as a function of product size and production rate. Power requirements were also related to theoretical equipment efficiencies.

Existing applications of size-reduction equipment to solid waste processing merely adapt standard equipment designed for other functions. Consequently, serious problems have been reported by solid waste processors. Based upon operational difficulties and engineering design considerations, new concepts were generated during the study for improved solid waste size-reduction equipment.

Due to the heterogeneity of typical solid waste and diversity of recovery operations which can be conceived, separation is a second important step in the recovery and utilization of solid waste. The efficiency with which separation is effected and the degree to which the desirable materials can be segregated are significant factors contributing to cost and marketability of recovered products. Consequently, significant effort was devoted to the collection of technical data for equipment and processes that could be used in the separation of solid waste.

As of 1968 the most widely employed means for separating solid waste is handpicking and sorting from conveyors. Handsorting is employed, almost without exception, at nearly all U.S. and European compost plants, and at some municipal incinerators, to remove such items as clean newsprint and cardboard, rags, metals, glass, and plastic. These materials are removed for salvage purposes and in the case of composting to upgrade the quality of the final product. Handsorting is unsatisfactory for large-scale recovery and utilization for several reasons including: (1) low salvage prices that limit the economic attractiveness of such operations; (2) the limited degree of separation that can be effected since a nominal size work force can be concerned only with removing more bulky pieces; (3) human fallibility.

In recognition of the need for a variety of improved separation techniques, and in view of the extremely limited number of existing applications of advanced technology to solid waste processing, the entire field of industrial separation technology was surveyed in detail for potentially adaptable techniques and related performance and cost characteristics. As indicated, only a small number of the more sophisticated separation techniques have been applied to solid waste processing, and the historical experience of these applications is extremely limited. Consequently, much of the collected cost and performance data relate to industrial applications significantly different from solid waste processing and must be employed and interpreted with extreme care. Such data, therefore, cannot be used for design purposes, but rather are intended to be used to indicate the general types of separations which are possible, general feed requirements, and order-of-magnitude costs. This type of information is essential in making preliminary judgments as to potentially desirable process and equipment combinations for solid waste recovery.

All of the separation techniques studied are designed to detect and to operate selectively on (and to a large extent automatically) differences in various properties of the materials being separated. Primary properties employed in the separation techniques investigated in this study include magnetic properties, particle size, specific gravity, and light-reflectance properties of the surfaces.

Specific separation processes studied included magnetic separation, eddy-current separation, flotation, dense-media separation, screening, vibrating tables (wet and dry), optical sorting, and ballistic separation. In principle each of these processes has potential application to processing. However, with the exception of magnetic separation, the degree to which these techniques can be adapted in practice is not well established because of the lack of suitable cost and performance data upon which to base evaluations. The primary technical obstacle in the application of these techniques to the separation and recovery of solid waste is that its components generally do not exhibit one unique property that permits straightforward separation.

The ultimate objective of both size reduction and separation is the recovery of solid waste, either in the form of new manufactured by-products or by direct salvage. Existing techniques, practices, and market situations for salvage of tin cans, paper, glass, plastics, rubber, rags, and incinerator residues from solid waste were investigated. Although a salvage market does exist and is being used in a few instances to recover selected fractions of solid waste, the long-term potential of direct salvage is not large. The primary problem relates to technical difficulties and the relatively high cost of obtaining sufficiently pure fractions to comply with salvage specifications and the relatively lower cost of raw materials which the salvaged products are supposed to replace. It is concluded, therefore, that the major potential for solid waste recovery is in the manufacture of new by-products.

Available cost and performance data were collected for four general areas of by-product recovery: composting, heat recovery, chemical recovery including biochemical processes, and fly-ash utilization. Composting along with its auxiliary salvage operations is the recovery process which is being employed most widely and for which most data are consequently available. Data have been collected on capital and operating costs, power requirements, and labor requirements for both U.S. and European compost plants. Data on municipal incinerators employing waste heat recovery are scarce. Actual experience in the United States is limited to installations in Chicago, Atlanta, Norfolk, Long Island, and Miami. Operational data were difficult to obtain, although sufficient data were available to develop preliminary relationships for capital costs. Chemical conversion of solid waste has not been practiced on a large scale, and available information is limited to laboratory data and process estimates. Studies conducted by others have indicated potential economic merit in the hydrolysis of solid waste containing 60 percent paper, and in the fermentation of mixed refuse to produce protein. Available cost estimates have not yet been substantiated by large operations. Detailed laboratory data have been made available by various researchers, for the pyrolysis of solid waste to produce fuel gases, carbon, and organic acids, but cost estimates have not yet been developed. A potential for the utilization of incinerator fly ash was also identified. This application may be limited, however, by the wide availability of coal fly ash which is a higher-quality, more uniform product.

Based upon the quantitative and qualitative data collected during the study, potential processes and equipment combinations are defined which appear sufficiently promising to warrant either additional development through research or further operational study at the demonstration level to obtain detailed performance and cost data of the type required for use in the design of future systems.

Based upon information collected, it is considered that solid waste recovery may never become economic in the engineering sense, but that the external diseconomies and social costs associated with the disposal-oriented methods of solid waste management may provide a strong motivation for continued development of solid waste recovery techniques. It is also concluded that meaningful and reliable cost data are not available from existing operations and that the Bureau of Solid Waste Management will need to collect such data from demonstration projects and similar activities conducted under its own auspices. A final major conclusion is that by-product manufacture from mixed refuse offers more economic potential for solid waste recovery than does material salvage.

The mention of commercial products within this report does not imply endorsement by the U.S. Government.

II. Introduction

WHAT TO DO with the more than 300 billion lb of municipal solid waste generated annually in the United States is a question receiving extensive attention at all levels of technology ranging from research to facility construction. Most current activity can be traced to authority delegated and financial resources made available by passage of the Solid Waste Disposal Act, PL 89–272, in October 1965. Furthermore, much of the recent activity has centered both on disposal of this great quantity of material and its utilization. This latter aspect of solid waste disposal, or more properly solid waste management, is the subject of this study. Specifically, the objective of this study was to prepare a handbook of equipment and process technology and associated costs that could be used in solid waste recovery and utilization. Studies focused on three main areas—size reduction, separation, and recovery. For purposes of this study, recovery includes both direct salvage and the manufacture of new by-products.

The current emphasis on the recovery and utilization of solid waste is the result of many factors. Perhaps most important is the growing inadequacy of traditional methods of disposal. Land areas suitable for landfill near urban centers where the bulk of the solid waste is generated are becoming increasingly scarce and more costly to obtain. Open burning has been outlawed in most major urban centers because of its contribution to air pollution.

Open dumping has also been stopped in most areas for a variety of reasons including health hazards, aesthetic considerations, and conditions that lead to insect and rodent proliferation and water pollution. Incineration, as traditionally practiced, is becoming increasingly less attractive due to expensive air pollution control equipment required to meet acceptable air-quality standards.

Another reason for investing considerable effort in the recovery and utilization of solid waste is that much of this material is, in effect, a resource disguised as a nuisance. For example, approximately 12 million tons of steel, mostly in the form of tin cans, are being lost every year in landfills as a result of our current waste disposal practices.* It makes sense from both economic and resource conservation viewpoints that better use be made of such materials. An analysis of the recovery and utilization potential of solid waste is deferred to the next section of this report.

Within the context of these considerations, this study was undertaken to define the technology, economics, and future potential for the recovery and utilization of municipal solid waste. Since these factors hinge largely upon costs and performance capabilities, emphasis was placed upon obtaining cost and performance data from literature, patent files, equipment manufacturers, and currently operating refuse reclamation and disposal plants. A previous study conducted by Battelle indicated that the published literature is not an adequate source of the cost performance data desired.[1] Consequently, heavy reliance was placed, as information sources, upon manufacturers and operators of equipment and processes that could be used in various aspects of solid waste recovery. During the study, over 200 such contacts were established. These are summarized in detail in Appendix A.

---

* $\frac{\text{0.825 tons refuse}}{\text{persons years}} \times 200 \times 10^6 \text{ persons} \times$

$\frac{\text{0.075 lb ferrous material}}{\text{lb refuse}} =$

$\frac{\text{12.375 tons ferrous material}}{\text{year}}$

Based upon equipment and process capabilities (and associated capital and operating costs) and expected ranges in solid waste characteristics, possible synergistic and antagonistic effects of one process upon another have been identified, and potentially promising process combinations have been suggested.

Problems encountered during the study related primarily to the lack of available data. Wherever possible, engineering estimating procedures were employed to fill data gaps. Where the generated estimates are not sufficiently reliable or could not be developed, recommendations are provided for specific programs designed to generate missing data either through research or demonstration study programs.

The work summarized in this report was supported by the Bureau of Solid Waste Management,* U.S. Department of Health, Education, and Welfare under contract Ph-86-67-265. Considerable assistance in the collection of information was also rendered by various manufacturers and operators of existing systems. Specific acknowledgements are indicated in the text and are summarized in Appendix A.

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*The Bureau is now the Solid Waste Management Office of the U.S. Environmental Protection Agency.

III. Recovery potential of solid waste

THE UNDERLYING PHILOSOPHY that has motivated this study is that solid waste is a resource. This philosophy is, however, meaningful only to the extent that techniques and processes can be developed to exploit this resource through the recovery of solid waste materials in an economically viable operation. The assessment of economic viability is by no means a simple task; however, one must not only consider processing costs in light of income and market potential of recovered materials, but must also consider social costs and, perhaps more important, social benefits associated with the alleviation of pollution, health hazards, and other problems associated with traditional disposal techniques. These latter considerations relating to the socioeconomic aspects of solid waste recovery are outside the scope of this study which has concentrated on technical performance of selected processes and direct processing costs.

TABLE 1

EXPECTED RANGES IN MIXED MUNICIPAL REFUSE COMPOSITION*

Component	Percent composition as received (dry weight basis)	
	Anticipated range	Nominal†
Paper	37–60	55
Newsprint	7–15	12
Cardboard	4–18	11
Other	26–37	32
Metallics	7–10	9
Ferrous	6–8	7.5
Nonferrous	1–2	1.5
Food	12–18	14
Yard	4–10	5
Wood	1–4	4
Glass	6–12	9
Plastic	1–3	1
Miscellaneous	<5	3
		100

Moisture content:
Range (percent) 20–40
Nominal (percent) 30

*Based upon data contained in References 2 to 8.
†Battelle estimate.

To provide a basis for evaluating the technical aspects and the engineering economics, it was necessary to establish guidelines regarding the typical composition of mixed municipal refuse.[*]

Recent studies have shown this to be highly variable according to geographic location, climate, season, and socioeconomic characteristics of the contributing population.[2, 3] Sampling difficulties also contribute to the difficulties in obtaining precise composition data.

Data collected from several sources on solid waste characteristics are considered to be a reasonable representation of available data (Tables 1 and 2).

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[*] In the broadest sense, municipal refuse is defined to include all waste materials that are not handled by air or waterborne carriers. Within this category fall all of the solid waste materials generated by domestic, commercial, institutional, and industrial operations as well as solid materials resulting from air pollution control (e.g., flyash), water pollution (sewer sludge), and miscellaneous material such as junk cars. In this handbook, the term "mixed municipal refuse" is used to cover the mixed solid materials resulting from household, commercial, and institutional garbage and trash collections, but excluding special industrial wastes, the larger demolition wastes, and specialty loads of like items (e.g., loads of rubber tires, junk cars, and sewage sludge). The mixed municipal refuse will be used as a basis for evaluating the technical and engineerng aspects of solid waste recovery since it provides the greatest challenge in terms of nonhomogeneity of constituents and difficulty in separation.

TABLE 2

DEFINITIONS OF MIXED MUNICIPAL REFUSE COMPONENTS[a]

Newsprint	Newspapers. Does not include magazines, handbills, etc.
Cardboard	Corrugated boxboard and the heavier paperboard used in cartons. Light cardboard in food packages and the backing of paper pads are included with "miscellaneous mixed paper."
Miscellaneous mixed paper	All other paper not included above.
Metallics	Tinned and aluminum cans, hardware, bottle caps, utensils, wire, and other ferrous and nonferrous metal articles.
Food (garbage) waste	Wastes, from the handling, preparation, cooking, and serving of foods. Does not include packaging materials or paper discarded with garbage.
Yard waste	Lawn, garden, and shrubbery clippings, sod and small yard debris other than branches.
Wood waste	Branches, scrap lumber, and other wooden articles.
Glass	Glass and ceramic materials.
Plastic	Film plastics and molded plastic articles.
Miscellaneous	Stones, metal oxides, articles made of natural and synthetic fibers, rubber products, and leather goods.

[a] Kaiser, E. R., and C. D. Zeit. The composition and analysis of domestic refuse at the Oceanside plant. Personal communication to N. L. Drobny, Aug. 1966.

IV. Size reduction

SIZE REDUCTION is becoming an increasingly important operation in municipal solid waste processing. Size reduction is of primary interest here because it permits more efficient separation and recovery processes. Of more general interest is the fact that reduction of material bulk often facilitates handling. Examples of the effects of particle size on the efficiency of separation is given in a later section on material separation. The Stoner, for example, a gravity separation device, requires closely controlled particle size to effect good separation. Similarly, the Osborne separator can tolerate organic particles no larger than 1 in. or inorganic particles no greater than $\frac{3}{16}$ in.

For many years, recovery from municipal solid waste was accomplished entirely by handsorting, and size reduction was applied only to such materials as oversize burnable waste and compostable material. In recent years, however, the combination of greater waste generation and increased costs from handsorting has resulted in the need for more mechanization to provide for recovery that is economical. This, in turn, has created a need for size-reduction equipment suitable for use on solid municipal waste.

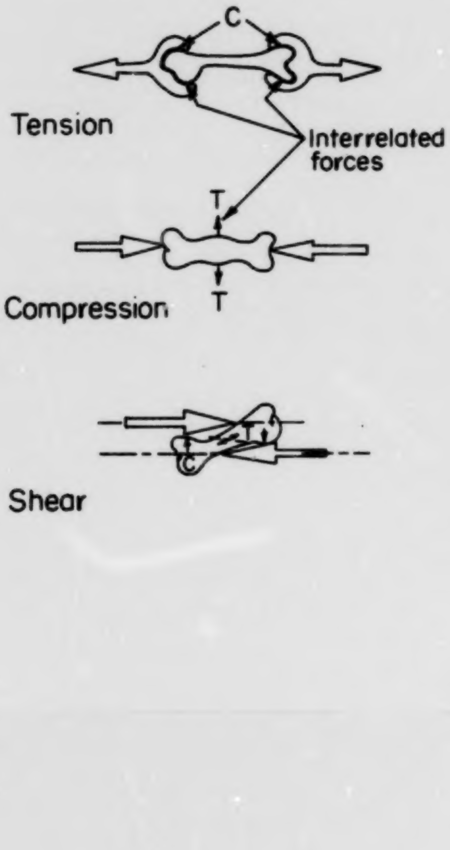

FIGURE 1. *The application of forces in size-reduction operations.*

PRINCIPLES OF SIZE REDUCTION

Size reduction of municipal solid waste is the mechanical separation of bodies of material into smaller pieces. Some minor biodegradation and water-dissolving effects are helpful in composting and wet-pulping processes, but size reduction by the application of mechanical forces is the focus of this discussion. These mechanical forces are categorized as follows: tension forces, compression forces, and shear forces (Figure 1).

TENSION FORCES

The application of tension to a body is usually accompanied by compression and shear forces as a result of gripping forces and the internal transfer of energy. The energy involved in the separation of a body into smaller pieces by tension forces is the force applied multiplied by the distance through which it moves. To separate a ductile body by tension forces, the energy required is theoretically greater when the length of the yielding member between the points of application of the forces is greater. Therefore, the closer together the opposing tension forces, the lower will be the breaking energy. Hammermills in which a hammer impacts a mass and breaks off a section are one example where tension forces develop at points separated by relatively small distances.

COMPRESSION FORCES

The fracture of a body by compression is usually caused by internal tension and shear forces that are a result of the compression force. Here again, the energy used is the force applied multiplied by the distance traveled. Strong, brittle materials—e.g., glass—

may require high forces for fracture such as those obtained by impact. The distance through which the force travels to bring the material up to the yield point may be very short, however, and this may result in relatively low theoretical power requirements.

SHEAR FORCES

Shear forces in a body are usually accompanied by both tension and compression forces (Figure 1). Compression forces are applied to a body in offset planes to produce a shearing action. Tension forces can result in the body due to the distance between the offset planes during the shearing operation.

The energy required to shear a body into smaller pieces is also the force applied times the distance through which the force is applied. The shearing of flat material (even if it is ductile) may be accomplished with a minimum of work because of the relatively short distance that the force travels. This suggests that emphasis on the use of shearing forces in municipal solid waste size reduction could lead to increased efficiency.

THEORETICAL POWER REQUIREMENTS

The power requirements for size reduction of ductile material by tension are, in general, higher than for brittle material because of the long stretching travel required to produce separation. Thus, in order to consider the more difficult task for comparison purposes, theoretical requirements were computed for reducing large sheets of 0.050-in. ductile steel to 6- and 3-in. squares.

The following simplifying assumptions were made: (1) 1-ton grip force to produce a 1-in. deep corrugation; (2) yield strength of 50,000 psi; (3) elongation of 20 percent; and (4) yield occurring for 3 in. on each side of the fracture line. The computations are as follows: force requirements to bring two sides of a square to the yield point are:

$$\text{The force required for 6-in. pieces} = 50{,}000 \times 0.050 \times 6 \times 2 = 30{,}000 \text{ lb}$$

$$\text{The force required for 3-in. pieces} = 50{,}000 \times 0.050 \times 3 \times 2 = 15{,}000 \text{ lb}$$

$$\text{Travel} = 0.2 \times 6 = 1.2 \text{ in. or } 0.1 \text{ ft}$$

$$\text{Clamping energy} = 2{,}000 \times \frac{1}{12} = 167 \text{ ft-lb or } 0.1 \text{ ft}$$

$$\text{Breaking energy for 6-in. pieces} = 30{,}000 \times 0.1 = 3{,}000 \text{ ft-lb}$$

and

$$\text{Breaking energy for 3-in. pieces} = 15{,}000 \times 0.1 = 1{,}500 \text{ ft-lb}$$

Now, 0.050-in. steel sheet weighs about 2 lb/ft²

$$\text{Pieces/ton} = \frac{2{,}000 \times 4 \text{ pcs/ft}^2}{2 \text{ lb/ft}^2} = 4{,}000, \text{ 6-in. pieces/ton}$$

and

$$\frac{2{,}000 \times 16}{2} = 16{,}000, \text{ 3-in. pieces/ton}$$

Power requirements per ton are:

$$\text{Power for 6-in. pieces} = \frac{4{,}000 \times 3{,}167}{33{,}000 \times 60} = 6.4 \text{ hp-hr/ton}$$

and

$$\text{Power for 3-in. pieces} = \frac{16{,}000 \times 1{,}667}{33{,}000 \times 60} = 13.5 \text{ hp-hr/ton}$$

The tearing of wood, as an example of a more easily reduced component of solid waste, may be compared to the tearing of steel by applying density, strength, and yield factors, and assuming the same piece sizes. Assuming relative densities of 0.28 lb/in³ for steel and 0.023 for wood, a strength ratio of 50,000 to 4,000 psi and a yield ratio of 20 to 10, theoretical power requirements for the size reduction of thin wood sheets to 6- and 3-in. squares would be as follows:

$$\text{Power required} = 6.4 \times \frac{28}{2.3} \times \frac{4{,}000}{50{,}000} \times \frac{10}{20} = 3.1 \text{ hp-hr/ton (6-in. wood)}$$

$$\text{Power required} = 13.5 \times \frac{3.1}{6.4} = 6.3 \text{ hp-hr/ton (3-in. wood)}$$

As expected, the actual power requirements discussed later under the heading "Existing and Estimated Performance Data" were found to be considerably higher than the theoretical values.

CURRENT EQUIPMENT DESIGNS

In the course of the program, 68 companies identified as manufacturers of size reduction equipment were contacted; these company contacts are summarized in Appendix A. Basic equipment types available from these manufacturers include: crushers; cage disintegrators; shears; shredders, cutters, and chippers; rasp mills; drum pulverizers; disk mills; wet pulpers; and hammermills.

All except cage disintegrators, cutters, and disk mills have direct potential applications in municipal waste size reduction, with hammermills being used in about 90 percent of the existing systems.

CRUSHERS

Four types of crushers are used in industry (Figure 2). These are jaw, roll, gyrating, and impact types. All four of these have potential uses in the solid waste program; however, the impact crusher, a form of hammermill, has the most universal application.

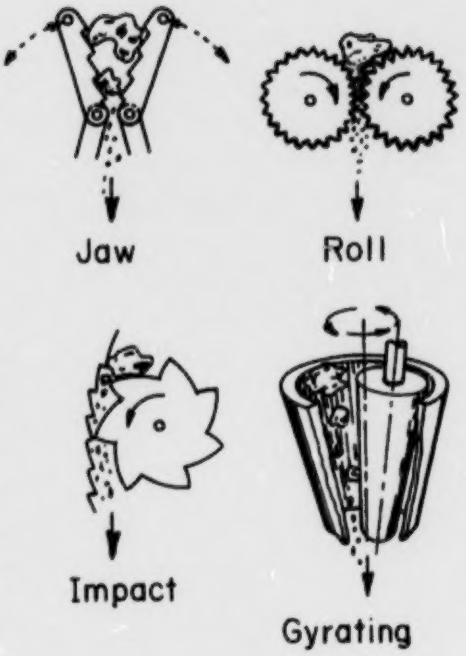

FIGURE 2. *Crushers.*

The jaw, roll, and gyrating crushers use the relatively slow efficient application of compression to friable materials such as coal and rock. General usage is in mines and quarries, and a wide range of product size, ½ to 10 in., may be obtained. Power may range as widely as 25 hp in the small units to 2,000 hp in huge mine installations.

CAGE DISINTEGRATORS

Cage disintegrators are high-speed machines which use single or multiple contrarotating cages to produce impact on material (Figure 3). Somewhat selective input is introduced at the center, and material is fractured on natural cleavage planes by the repeated action of the heavy cage bars as it escapes radially. This action produces rapid, efficient application of compression; but, as in the case of most of the crushers, it is limited to brittle materials such as glass and rock salt. Cage disintegrators are used primarily in chemical industries with a product ranging from fine powder to ½-in. pieces. The usual range of power is from 2 to 1,000 hp. The most suitable application of cage disintegrators

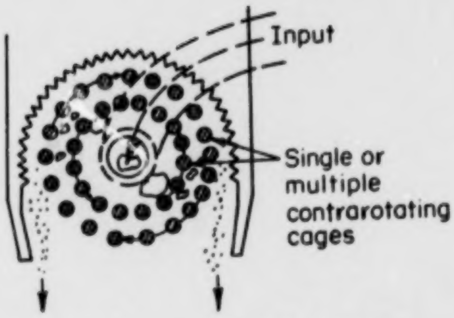

FIGURE 3. *Cage disintegrators.*

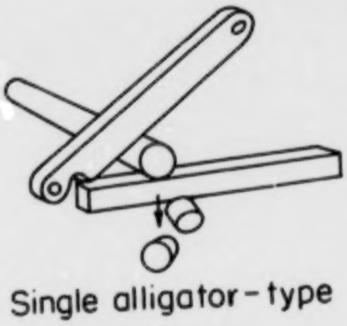

FIGURE 4. *Shears.*

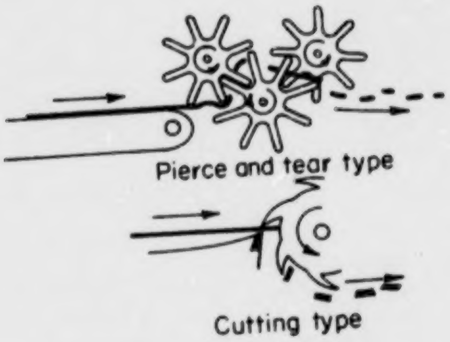

FIGURE 5. *Shredders, cutters, and chippers.*

to solid waste size reduction would be in secondary size reduction of separated, friable materials.

SHEARS

The single-blade shear is an illustration of a class of size-reduction equipment which is directly applicable to solid waste (Figure 4). Shears may range from the small, single-blade, alligator type to the large, multiple-blade hopper type. As the name implies, shears employ the slow application of shear forces. Use of shears is somewhat limited to bulky materials such as wood timbers found in demolition and harbor waste and metal automobile bodies.

Single-blade shears are often found in scrap-metal yards where they are used on a wide range of materials from drive shafts and I-beams to automobile bodies. Multiple-blade shears are often used for automatic reduction of trees and other oversize items.

The product normally ranges from 1-ft cubes to auto bodies cut into thirds. Applications to municipal solid waste would, in general, be primary size reduction operations.

SHREDDERS, CUTTERS, AND CHIPPERS

Shredders, cutters, and chippers utilize both tension and shear. In this class of equipment, two general types are of interest—the pierce-and-tear type and the cutting type (Figure 5). Although the cutting type is more widely used in industry, it is not well suited to the reduction of municipal solid waste. Its blades properly sharpened for good efficiency are excessively vulnerable to damage by unsorted solid waste.

The pierce-and-tear type of shredder uses overlapping fingers operating at various speeds—slow, medium, fast—to pierce, tear, and shear. This machine uses the interaction of relatively dull members to apply a tearing action.

In general, the application of tension and shear by piercing and tearing is best suited to fibrous or ductile materials as found in the paper and boxboard industries. Of more direct use on municipal solid waste, however, are the more familiar mobile yard-waste chippers and the large auto-body shredders.

Power inputs to shredders of interest in municipal solid waste processing range from 100 hp on the small units to 2,000 hp on the large hammermills.

RASP MILLS

Rasp mills are massive cylindrical machines, 20 ft or so in diameter, which employ the slow application of all three forces—tension, shear, and compression (Figure 6).

The input to the rasp mill is flexible. Through a large opening, a wide range of solid waste can be introduced.

An internal rotor, traveling at 5 to 6 rpm, swings heavy arms which push the waste around and around over rasping pins and down through holes to produce about 2-in. product.

Thus, the mill is self-limiting; and, after a reasonable length of time, durable bulky items which have not been properly reduced are turned out through a reject chute.

Rasp mills, like drum pulverizers, are used primarily in composting plants. The only rasp mill found in the United States during this study was the one in the joint U.S. Public

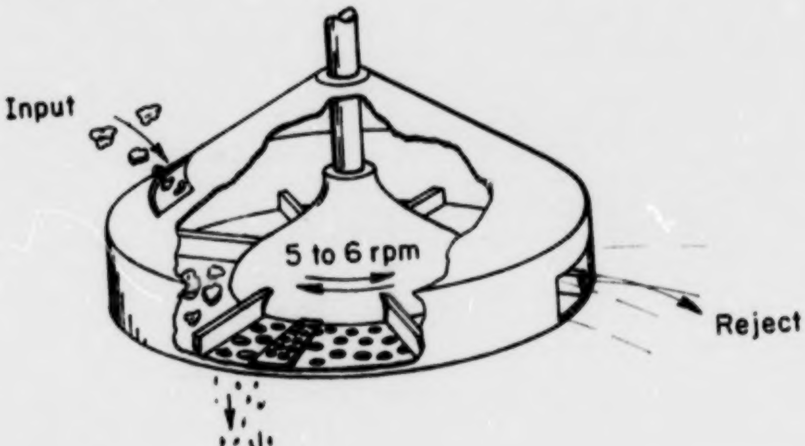

FIGURE 6. *Rasp mills.*

Health Service–Tennessee Valley Authority composting project at Johnson City, Tennessee. However, it is reported that several are being used in Europe[9] and one in Tel Aviv, Israel.[10]

DRUM PULVERIZERS

Drum pulverizers have an action similar to the rasp mill (Figure 7). The input is flexible, again accepting a wide range of materials. These materials pass through a rotating drum about 10 ft in diameter. The drum may be circular, octagonal, or hexagonal in design and may rotate at speeds up to 11 rpm. Drum pulverizers may have added churning effects by the action of stationary or contrarotating beaters or baffles. Reducible material is torn and pushed through the holes which may be the same size or graduated. As the material passes through the drum longitudinally, a rough size separation may be provided.

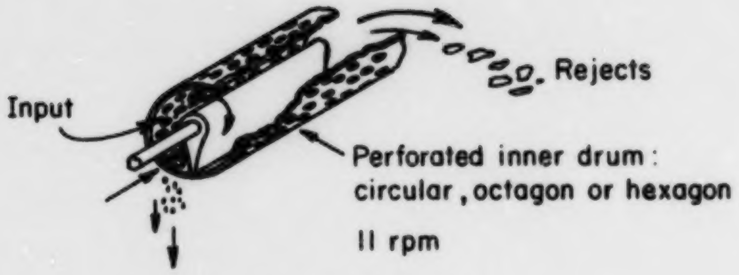

FIGURE 7. *Drum pulverizers.*

DISK MILLS

Disk mills are a class of precise machines with very high-speed single or contrarotating disks between which selected material is passed (Figure 8). The material is literally torn to bits. Disk mills are best suited to pulpable materials, although other materials such as flour and sugar are processed in them.

Their applications are limited to relatively small input sizes—perhaps 2-in. maximum. They are used extensively in the paper, boxboard, and food production industries. Their product is usually a refined pulp or fine grain.

Possible applications of disk mills to municipal solid waste could be considered as a secondary size-reduction operation on pulpable materials. Power up to 4,000 hp on these machines is not unusual in large paper mills. Smaller models of these machines appear to be more applicable to municipal solid waste.

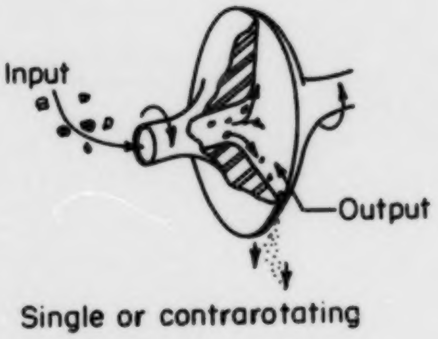

FIGURE 8. *Disk mills.*

WET PULPERS

Wet pulpers are similar to single-disk mills except they have vertical axes (Figure 9). In operation, a slurry of about 90 percent water and somewhat selected waste produces a toroid in which the solids are subject to repeated impact by hardened high-speed members. These members normally operate at a speed of about 5,000 ft per min. Thus, the rapid application of all three forces is attained. Wet pulpers are best suited to fibrous material, although a wide range of material including occasional cans and

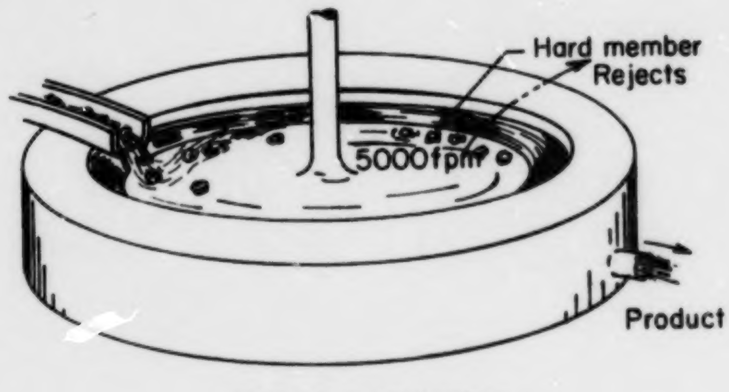

FIGURE 9. *Wet pulper.*

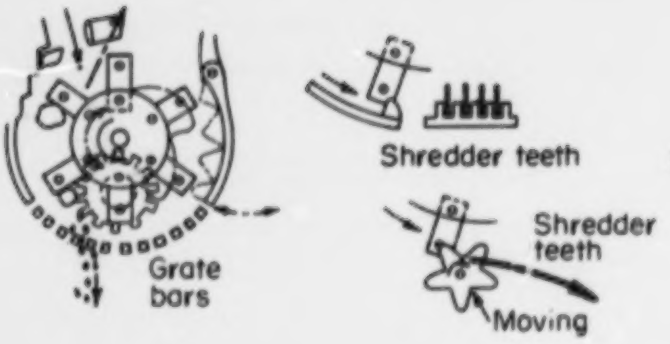

FIGURE 10. *Hammermills.*

rocks can be tolerated. Unpulpable material, such as rubber tires, is rejected. Barbed wire type of conveying devices called raggers are often used for automatic extraction of rope and fabric; but to date, they are somewhat limited to more selective input. Bar screens in the output stream also have been used, but tend to clog with general solid waste input. As a result of the buildup problem, conveyor-type screens have been considered. Applications to municipal solid waste processing are primarily in composting plants; however, the characteristics of the product have been cited as readily adaptable to separation, recovery, and landfill operation.

HAMMERMILLS

Hammermills, as mentioned before, represent the largest percentage of municipal waste size-reduction equipment (Figure 10).

There are two general types of hammermills—the swing-hammer type and rigid-hammer type. Pivoted swing hammers may vary considerably in design from the rectangular block type, to sharp choppers and flexible flails, to the ring-hammer with multiple wearing corners. Rigid hammers fixed to the rotor also have a wide range of designs from thin, sharp choppers to the wide, blunt impact-crusher type. Clearance adjustment of the impact surfaces and swinging tramp-metal traps are often provided. On some hammermills, plate-conveyor-type impact surfaces are added to provide extended wearing surfaces plus an antijamming effect.

Another variation is the combination of standard hammermill action with the use of shredding members meshing with the hammers. These may be stationary or moving (Figure 10). Usually grate bars determine the product size, but some designs use the clearance of the hammers with impact surfaces or shredder teeth and machine speed to determine the product size.

Hammermills make use of rapid application of tension, compression, and shear forces. A ballistic presorting or rejecting effect can be obtained by upswinging hammers. In this mode of operation, durable bulky items are bounced by the hammers into the reject bins or chutes. Another design, which uses a unique vertical axis rotor, rejects unwanted material by flinging it up a conical surface into a reject area.

Hammermills have, perhaps, the widest range of feed in regard to material composition; but the adjustment of feed rate is critical for efficient operation. Information obtained on size reduction of municipal solid waste by the hammermill is quite variable because of wide variations in operating conditions.

MAJOR APPLICATIONS IN SOLID WASTE PROCESSING AND RELATED INDUSTRIES

Of primary concern in this project is the universal processing of mixed municipal refuse; useful information was also obtained, however, on the size reduction of selected materials such as wood and steel car bodies.

Twenty-one of the 68 companies contacted provided performance data on equipment currently applied to some portion of solid waste size reduction.* The equipment discussed here are hammermills, 14 companies; shredders, two companies; drum pulverizers, two companies; wet pulpers, two companies; and rasp mills, one company. Other types of equipment such as chippers and cage disintegrators may be applied to a minor portion of solid waste size reduction, but the more universal types were emphasized in this program. The specific companies contacted regarding size-reduction equipment are listed below.

Hammermills

American Pulverizer Company
St. Louis, Missouri

Buffalo Hammermill Corporation
Buffalo, New York

Buhler Brothers (Swiss)
Ontario, Canada

Ferrox Corporation
Scott, Louisiana

Heil Company (Gondard, French)
Milwaukee, Wisconsin

Gruendler
St. Louis, Missouri

Hammermills, Inc.
Cedar Rapids, Iowa

Hazemag U.S.A. (German)
New York City

Jeffrey Manufacturing Company
Columbus, Ohio

Newell Manufacturnig Company
San Antonio, Texas

Pennsylvania Crushers
Broomall, Pennsylvania

Stedman Foundry and Machine
Aurora, Indiana

Tollemache, Ltd.
London, Englar

Williams Patent Crushe and Pulverizer Company
St. Louis, Missouri

Shredders

Centriblast Corporation
Subdivision of Joy Manufacturing Company
Pittsburgh, Pennsylvania

Logemann Brothers
Fond du Lac, Wisconsin

Drum Pulverizers

John Thompson Company
England

Vickers Company
England

Wet Pulpers

French Oil Mill Company
Piqua, Ohio

Black Clawson Company
Middletown, Ohio

Rasp Mills

Dorr-Oliver Company
Netherlands

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*Full address, contacts, and types of data are presented in Appendix A.

TABLE 3

SOLID WASTE SIZE-REDUCTION EQUIPMENT IDENTIFIED

Identification*	Capital investment (thousands of dollars)	Horsepower	Material handled †	Average capacity (tons/hr)	Hp-hr per ton	Weight (tons)	Inlet opening (in.)	Special features, installations
①	35.0	800	MSW	17	47	25	55 x 60	Ring hammers, Erie, Tampa.
②	8.5	300	Dry to wet fibers.	40	7.5	10	50 x 50	Ring hammers, no bulky items.
③	33	200	Picked MSW	10	20		38 x 79	Double rotor, Europe.
④	80	350	MSW	30	12	19	48 x 60	Crushing feeder, 4-in. product, Meshing hammer/anvil, Gainesville.
	130	1,500		70	21	33	48 x 72	
5	50	80	Picked MSW	9	8.9		48 x 48	Rasp mill, 2-in. product, Johnson City, Tennessee.
⑥		1,000	Car bodies	20	50		40 x 80 Estimate.	Flattened car, Scott, Louisiana.
⑦	30	150	Picked MSW	10	15		40 x 40	Ballistic reject, Madison, Wisconsin.
⑧		350	Picked MSW	20	18			Plate-conveyer impact area, Mobile, Alabama.
⑨	60	800	Car bodies	25	32	35	42 x 60	Car bodies, Toledo, Ohio.
⑩	86	300	MSW	30	10	52	60 x 120	Rigid hammers, Impact crusher, New York City.
	160	800	Harbor waste	140	5.7	100	96 x 150	
⑪	17.5	150	Wood waste	30	5.0		42 x 48	Semiblunt hammers.
⑫	150	2,000	Presheared car bodies.	50	40	75	40 x 60	V-shaped hammers meshing with rotating grate; gripping feed to 12-in. from hammers, Fond du Lac, Wisconsin.
⑬	200	500	Car bodies	10	50		60 x 80 Estimate.	Feed rollers flatten the car bodies, San Antonio, Texas.
		1,000		16	62			
		1,500		20	75			
		4,000		50	80			
⑭	59.5	800	MSW	40	20	45	66 x 80	6-in. product (2 stages required for 1¼-in. product).
⑮	14.2	300	Wood waste	24	12	15	36 x 72	Semiblunt hammers.
16		50	Picked MSW	7	7			Drum pulverizers, 2-in. product, England.
⑰	53.0	150	Picked MSW	10	15			Vertical shaft, ballistic reject, England.
18		60	Picked MSW	8	7.5			Drum pulverizer, 2-in. product, England.
⑲	10	150	Picked MSW	10	15			Johnson City, Tenn., Los Angeles, and Cleveland.
		4,000	Car bodies	100	40			
20	15.0	150	Picked MSW	12	12			Wet pulper, 6-in. input 1-in. product, Altoona, Pa.
21	69.5	350	Picked MSW	60	6			1-in. product, 6-in. input, wet pulper.

*Manufacturer's code. See Table 4.
†MSW, Municipal solid waste.

EXISTING AND ESTIMATED PERFORMANCE DATA

Performance data have been collected on 27 size-reduction machines manufactured by the 21 companies (Tables 3 and 4). The data presented are mostly from manufacturers' ratings, to a limited extent from existing installations, and theoretical calculations outlined earlier (Figure 11 and Table 3). Users' data are available on some of the equipment and give general trend information.

The upper shaded area on Figure 11 includes size-reduction equipment applied to metal automobile-body size reduction. The lower shaded area includes equipment processing typical of mixed municipal refuse. Between these two areas falls equipment processing other bulky material such as harbor waste. Below both cross-hatched areas fall machines operating on selected solid waste or on wood products. Comparing the performance of Machines 12 and 13 having power requirements of 40 and 80 hp-hr per ton with the theoretical requirement of 6.4 hp-hr per ton for reducing steel to 6-in. pieces, the theoretical efficiencies of Machines 12 and 13 are only 8 and 16 percent. The size reduction of wood, in contrast, indicates relatively high efficiencies. For example, Hammermills 2 and 11, requiring 7.5 and 5 hp-hr per ton, respectively, would have efficiencies of 41 and 62 percent based on theoretical power requirements of 3.1 hp-hr per ton.

Direct comparisons of individual equipment items are impractical because of the wide range of materials, machine size, and product size represented (Table 3 and Figure 11). Nevertheless, higher unit power requirements (hp-hr per ton) of the larger

TABLE 4

MANUFACTURERS' CODE NUMBERS

○ Hammermills
□ Drum Pulverizers and Wet Pulpers
△ Rasp Mill
⬡ Shredders

①	American Pulverizer Company, St. Louis, Missouri.
②	Buffalo Hammermill Corporation, Buffalo, New York.
③	Buhler Brothers (Swiss), Ontario, Canada.
4	Contriblast Corporation, Subdivision of Joy Manufacturing Company, Pittsburgh, Pennsylvania.
5	Dorr-Oliver, Netherlands.
⑥	Ferrox Corporation, Scott, Louisiana.
⑦	Heil Company (Gondard, French), Milwaukee, Wisconsin.
⑧	Gruendler, St. Louis, Missouri.
⑨	Hammermills, Inc., Cedar Rapids, Iowa.
⑩	Hazemag, U.S.A. (German), New York City.
⑪	Jeffrey Manufacturing Company, Columbus, Ohio.
12	Logemann Brothers, Fond du Lac, Wisconsin.
⑬	Newell Manufacturing Company, San Antonio, Texas.
⑭	Pennsylvania Crushers, Broomall, Pennsylvania.
⑮	Stedman Foundry and Machine, Aurora, Indiana.
16	John Thompson Company, England.
⑰	Tollemache, Ltd., London, England.
18	Vickers Company, England.
⑲	Williams Patent Crusher & Pulverizer Company, St. Louis, Missouri.
20	French Oil Mill Company, Piqua, Ohio.
21	Black Clawson, Middleton, Ohio.

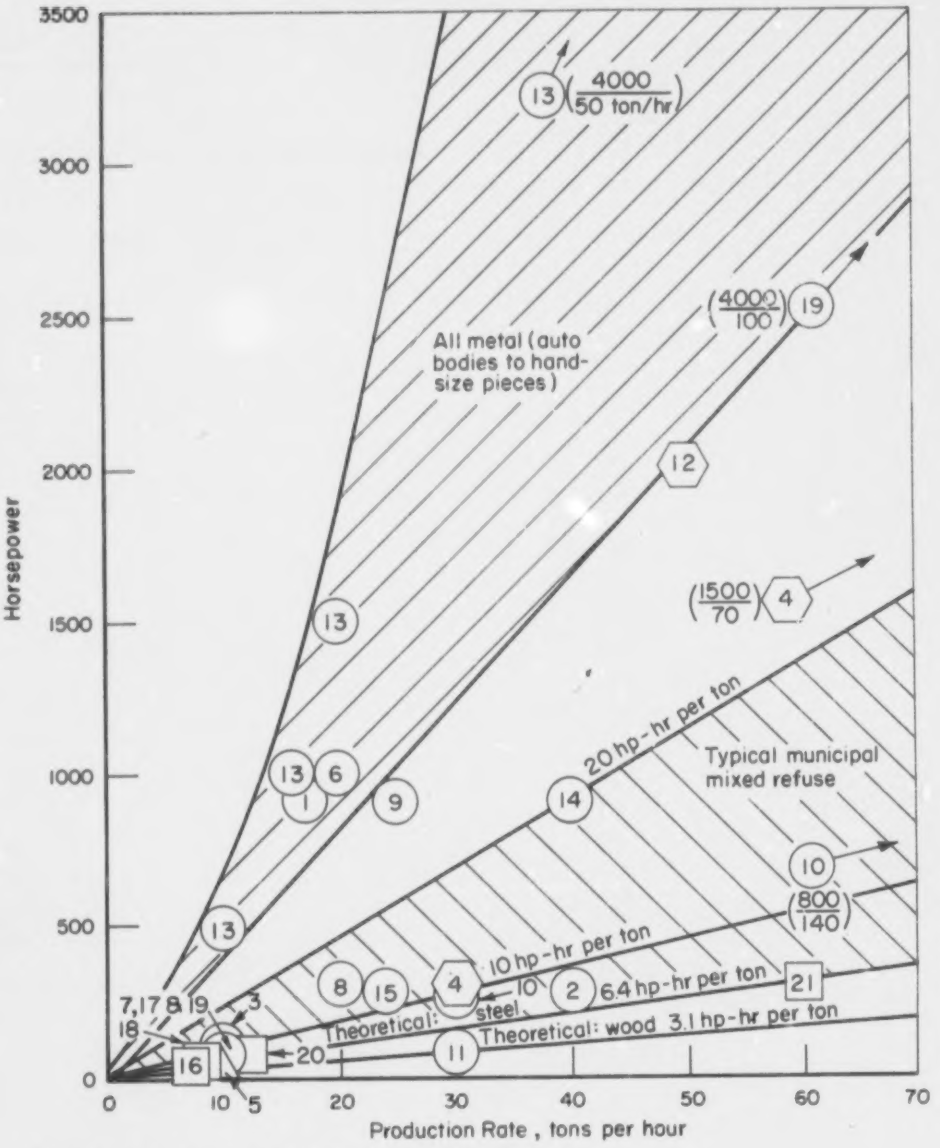

FIGURE 11. *Size-reduction power requirements.*

machines of the same manufacture indicate that the smaller machines may be more efficient. For example, the hp-hr per ton on increasing sizes of machines, e.g., 4, 13, and 19, are all higher for the larger machines (Table 3). Combinations such as preliminary shearing operations, crushing feeders, or shredding members in hammermills show synergistic effects on municipal solid waste. Shears, for example, would be too slow for thorough size reduction, but they do provide an input to some hammermills which could not otherwise be utilized.

Of the 27 machines with applicable power data, six had data based on unsorted municipal solid refuse, 10 had data based on processing sorted waste, and the remainder had data based on either wood only or metal car bodies. The following input-material factors were derived by averaging the hp-hr per ton values for each of the above materials and relating them to 1.00 for municipal solid waste: selected municipal solid waste, 1.00; sorted municipal solid waste, 0.65; wood (or fibers) only, 0.43; and automobile bodies, 2.82.

The product size is also a very important factor in size reduction. For a homogeneous material, the classical relationship of power-to-surface area is often applied; but on a heterogeneous mass, like municipal solid waste, experimental data indicate the following product-size factors: 6-in. sq pieces, 1.00; 4-in. sq pieces, 1.39; 2-in. sq pieces, 1.64; and 1-in. sq pieces, 2.38. Applying the input-material and product-size factors to the available data, the adjusted performance data were prepared as listed (Table 5). The same power ratings used in Table 3 are listed in Table 5 with capacity adjusted to an equivalent 6-in. sq mixed municipal solid waste.

TABLE 5

ADJUSTED PERFORMANCE AND COST DATA

	Horsepower	Capital investment (thousands of dollars)	Adjusted capacity (tons per hr)	Adjusted power requirements (hp-hr per ton)*	Adjusted unit capital investments (dollars per ton-per-hr capacity)
①	800	35. 0	17×1=17	47	2, 060
②	300	8. 5	40×0.43=17	19	500
③	200	33	10×0.65=6.5	31	5, 080
④	350	80	30×1.39=42	8. 3	1, 900
	1, 500	130	70×1.39=97	15. 5	1, 340
5	80	50	9×0.65×1.64=10	8. 0	5, 000
⑥	1, 000	----------	20×2.8=56	17. 8	----------
⑦	150	30	10×0.65=6.5	23	4, 620
⑧	350	----------	20×0.65=13	27	----------
⑨	800	60	25× 2.8=70	11. 4	857
⑩	300	86	30×1=30	10	2, 870
	800	160	140×1=140	5. 7	1, 140
⑪	150	17. 5	30×0.43=13	11. 5	1, 310
⑫	2, 000	150	50×2.8=140	14. 3	1, 070
⑬	500		10×2.8=28	17. 9	7, 150
	1, 000	200	16×2.8=45	22	4, 450
	1, 500		20×2.8=56	27	3, 570
	4, 000		50×2.8=140	29	1, 430
⑭	800	59. 5	40×1=40	20	1, 490
⑮	300	14. 2	24×0.43=10	30	1, 420
16	50	----------	7×0.65×1.64=7.5	6	----------
⑰	150	53. 0	10×1=10	15	5, 300
18	60	----------	8×0.65×1.64=8.5	7	----------
⑲	150	10	10×0.65=6.5	23	1, 540
	4, 000	----------	100×2.8=280	14	----------
20	150+(12×15)=330	15. 0	12×2.38=28.56	11. 8	536
21	350+(60×15)=1, 250	69. 5	60×2.38=143	8. 8	485

*Primary size-reduction power added.

Approximate purchase prices were obtained on 19 of the machines and unit machine costs were calculated (Table 5). The wide spread of adjusted unit machine costs, from $500 to over $7,000 per ton per hr is attributed to the variety of pricing methods and machine designs. For example, Machine 2 is a light-duty unit for wood only; Machine 13 is a heavy-duty machine for steel. The graph of these unit machine costs versus the adjusted capacity indicates the general trend of the unit cost of size-reduction equipment (Figure 12).

When performance data are plotted (Table 5 and Figure 13), the data scattering is much less than that of the theoretical data (Figure 11), indicating that the rough correction factors provide a means of making the data more useful. The large grouping of machines near the origin on Figure 13 includes many small machines of different types.

EXISTING AND ESTIMATED COST DATA

Twelve of the companies contacted provided cost data applicable to size reduction of municipal solid waste. Two Demonstration Grant Projects sponsored in part by the Bureau of Solid Waste Management provided complementary data on two types of size-reduction equipment—the rasp mill at Johnson City, Tennessee, and a hammermill at Madison, Wisconsin.

The combined data in four categories, based on potential yearly production, have been summarized (Table 6). The production is computed by assuming single 8-hr shifts for 5½ days per week, 52 weeks per yr (tons per hr x 8 x 286). The following were also assumed: maintenance, manufacturers' data modified by users' information and estimates from averages of similar equipment; equivalent annual cost, 6 percent, 10 yr; power, 1 cent/hp-hr; and labor, $10,000/yr.

Total costs from Table 3 can be re-

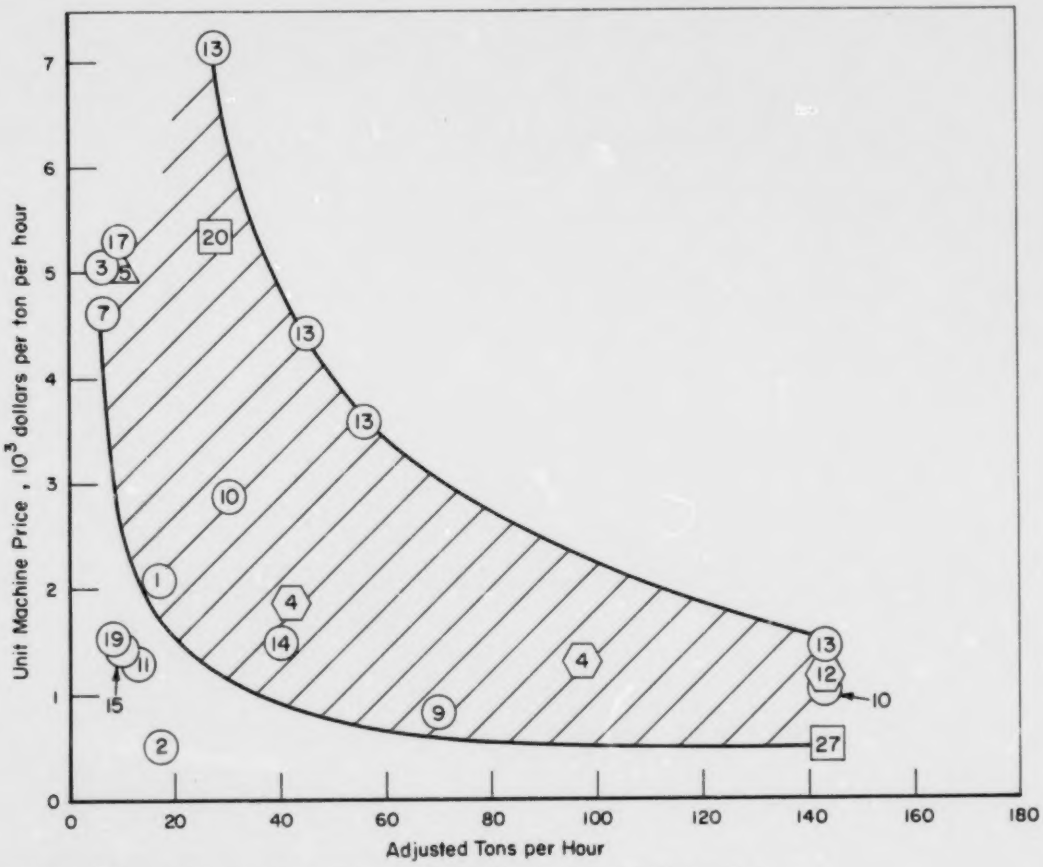

FIGURE 12. *Unit machine price versus adjusted production rate.*

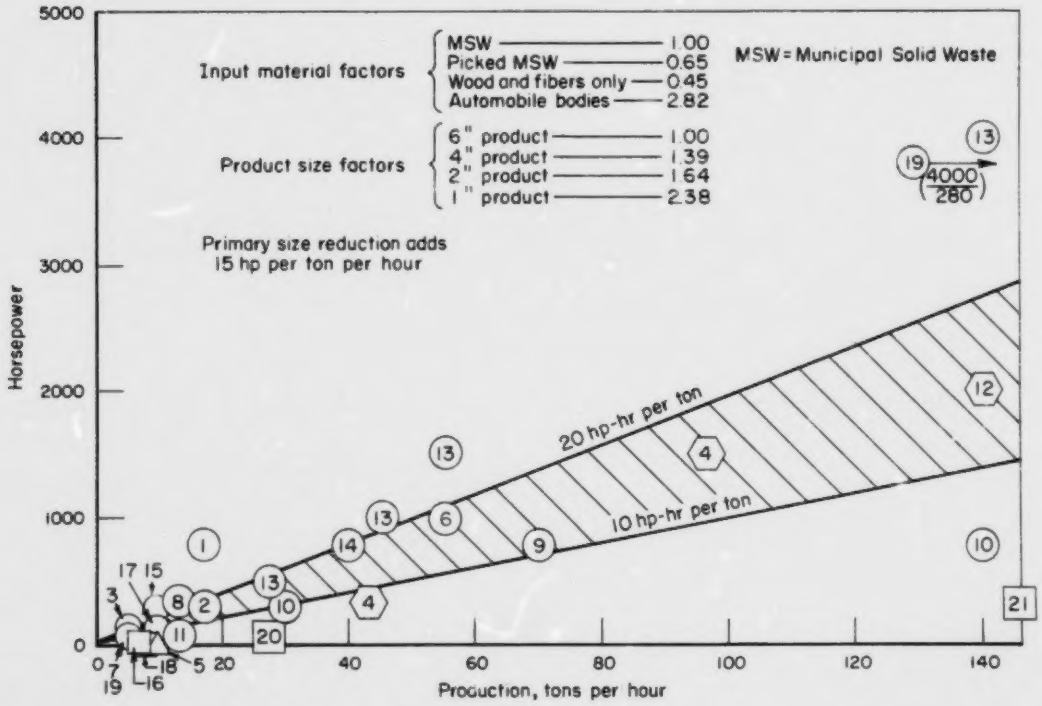

FIGURE 13. *Adjusted power requirements.*

TABLE 6

APPROXIMATE SIZE-REDUCTION COSTS*

Capacity† (tons per hr.)		Nominal product size (in.)	Costs (dollars per ton)					Variations from packer-truck input
			Mainte-nance	Equivalent annual cost	Power	Labor	Total	
①	17	6	0. 22	0. 12	0. 45	0. 25	1. 04	Bulky waste included.
②	40	6	0. 05	0. 22	0. 08	0. 11	0. 46	Wood only (nonbulky).
③	10	6	0. 27	0. 19	0. 19	0. 41	1. 06	Twelve percent prepicked.
4	30	4	0. 27	0. 20	0. 18	0. 17	0. 82	Some bulky extras; 4-in. product.
5	9	2	0. 06	0. 33	0. 09	0. 48	0. 96	Thirty percent durable bulky items rejected.
(7A)	10	6	0. 18	0. 18	0. 15	0. 43	0. 94	
(7B)	7. 2	4	0. 25	0. 25	0. 21	0. 61	1. 32	Ten percent reject of durable items.
(7C)	6. 1	2	0. 28	0. 29	0. 25	0. 72	1. 54	
⑨	25	6	0. 55	0. 14	0. 32	0. 18	1. 19	Bulky waste included.
⑩	30	6	0. 55	0. 17	0. 10	0. 14	0. 96	Harbor waste.
12	50	6	1. 10	0. 18	0. 40	0. 09	1. 77	Auto bodies.
⑭	40	6	0. 55	0. 09	0. 20	0. 11	0. 95	Bulky waste included.
20	12	1	0. 11	0. 08	0. 13	0. 36	0. 68	Premilled input.
21	60	1	0. 11	0. 08	0. 06	0. 08	0. 33	Premilled input.

*These costs are based on manufacturers' data modified by users' data and do not include site costs, crane costs, or other handling costs.
†Tons per year=average tons per hr x 8 x 286.

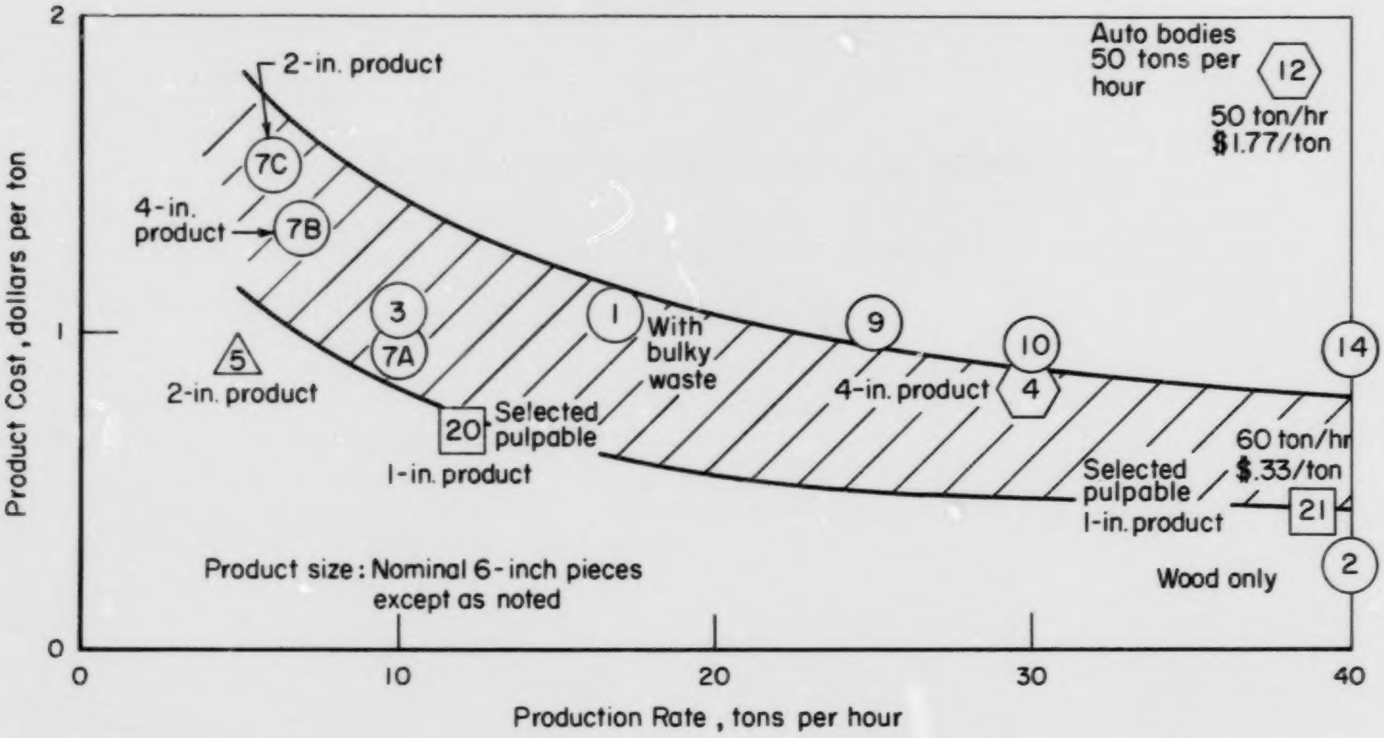

FIGURE 14. *Cost of size reduction versus production rate.*

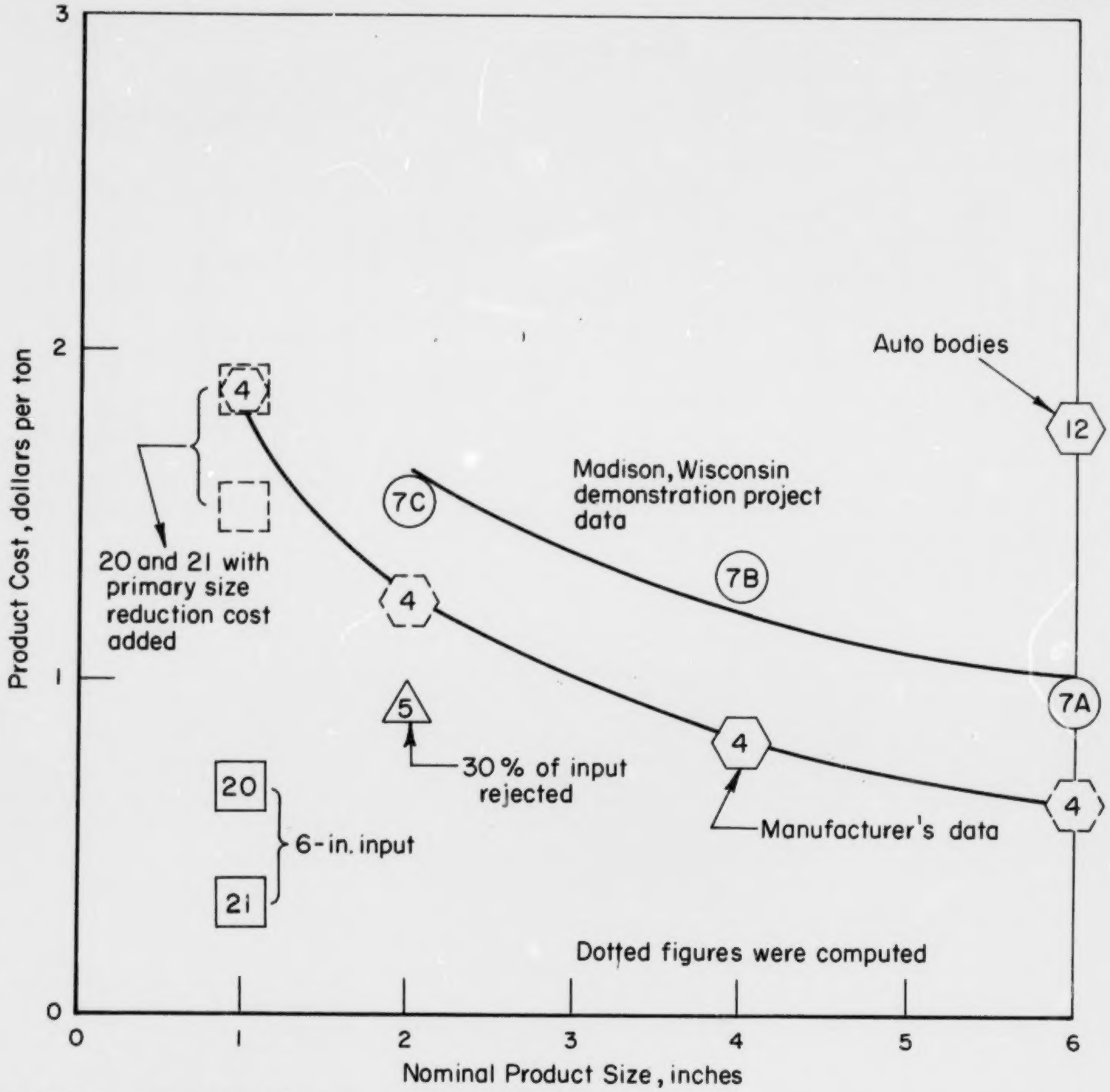

FIGURE 15. *Size-reduction cost versus nominal produce size.*

lated to production rate in tons per hr (Figure 14). As with the power data, the cost data show considerable scattering. The shaded area includes equipment for processing the range of materials from selected waste through bulky waste which may be found in municipal solid waste. The boundaries of the shaded area derived from the "six-tenths" factor for capital costs as follows:

$$\frac{\text{Cost}_2}{\text{Cost}_1} = \left(\frac{\text{Capacity}_2}{\text{Capacity}_1}\right)^{0.6}$$

$$\frac{\text{Unit cost}_2}{\text{Unit cost}_1} = \frac{\text{Cost}_2/\text{Capacity}_2}{\text{Cost}_1/\text{Capacity}_1} = \left(\frac{\text{Capacity}_2}{\text{Capacity}_1}\right)^{-0.4}$$

The data plotted exhibit the general trend indicated by this relationship.

Product costs from Table 5 versus product size may be plotted (Figure 15). Here again, the increasing cost trend with smaller product size roughly follows the 0.6 exponent relationship. An extra cost of $1.20 per ton is added to the 1-in. wet pulper product cost to account for a preliminary size-reduction operation. The dotted figures give theoretical costs for product sizes other than reported and were computed using the above equation.

To acquire comparable data on product costs from the various types

TABLE 7

ADJUSTED SIZE-REDUCTION COSTS*

	Nominal product size (in.)	Input material	Capacity (tons/hr)	Combined size and material factors	Adjusted (tons/hr)	Approximate capital (cost × $1,000)	Costs (dollars per ton)					
							Maintenance	Power	Labor	Maintenance, power, and labor costs	Amortization	Total of all costs
①	6	M†	17	1. 00	17	35	0. 22	0. 47	0. 25	0. 94	0. 12	1. 06
②	6	W	40	0. 43	17	8. 5	0. 05	0. 18	0. 26	0. 49	0. 03	0. 52
③	6	P	10	0. 65	6. 5	33	0. 27	0. 31	0. 64	1. 22	0. 30	1. 52
4	4	M	30	1. 39	42	80	0. 27	0. 13	0. 12	0. 52	. 14	0. 66
5	2	P	9	1. 07	10	50	0. 06	0. 08	0. 45	0. 59	0. 31	0. 90
7A	6	P	10	0. 65	6. 5	30	0. 18	0. 23	0. 67	1. 08	0. 27	1. 35
7B	4	P	7. 2	0. 90	6. 5	30	0. 25	0. 23	0. 67	1. 15	0. 27	1. 42
7C	2	P	6. 1	1. 07	6. 5	30	0. 28	0. 24	0. 67	1. 19	0. 27	1. 46
⑨	6	A	25	2. 82	70	60	0. 55	0. 11	0. 07	0. 73	0. 06	0. 79
⑩	6	M	30	1. 00	30	86	0. 55	0. 10	0. 14	0. 79	0. 17	0. 96
12	6	A	50	2. 82	140	150	1. 10	0. 14	0. 04	1. 28	0. 07	1. 35
⑭	6	M	40	1. 00	40	60	0. 55	0. 20	0. 11	0. 86	0. 09	0. 95
20	1	PG	12	1. 41	28	15	0. 11	0. 06	0. 16	0. 33	0. 04	1. 57‡
21	1	PG	60	1. 41	143	87	0. 11	0. 03	0. 05	0. 19	0. 04	1. 23‡

*These costs are based on those from Table 3 and adjusted to unsorted municipal solid waste reduced to a nominal 6-in. product by the application of the combined size and material factors.

† M = municipal solid waste, W = wood or fibers, P = picked municipal solid waste, A = automobile bodies, and PG = picked municipal solid waste preground to 6-in. size.

‡Includes $1.20 for cost of primary grinding.

of equipment while operating under more comparable conditions, the cost data were adjusted to bring all machines to municipal-solid-waste and 6-in.-product levels. Table 7 presents the adjusted size-reduction costs, applying the input-material and size factors.

Approximate capital costs of the basic size-reduction units with capacities adjusted to the theoretical value for unsorted municipal solid waste input and a 6-in. product have been plotted (Figure 16). Although the data are still scattered, the trend indicates that the capital cost of size-reduction equipment in general does not increase linearly with capacity, but follows the classical 0.6 exponent relationship.

Maintenance, power, and labor costs per adjusted ton capacity as totaled in Table 7 have also been summarized (Figure 17).

As pointed out in previous sections of this report, the municipal solid waste size-reduction cost figures presented are widely variable because of the wide variation in machines, material, and product size.

FINDINGS

Two trends are apparent from the investigations conducted during this study. (1) The demand on the tonnage or throughput capabilities of individual equipment items is increasing; (2) The capability of equipment is being increasingly challenged by the heterogeneity of the diverse materials to be processed.

These trends are attributed to both the population increase and the elevated standard of living. Both factors contribute to increased waste generation, and the latter results in a greater variety of material in municipal solid waste. Higher living standards contribute to demands for more efficient waste management, but in decreasing the incentive for manual presorting of municipal refuse.

PRINCIPLES OF SIZE REDUCTION

In summarizing the principles involved in size reduction, the forces utilized and the distances these forces must move are of prime consideration. The theoretical minimum energy requirements for size reduction of most of the components in municipal solid waste is considerably lower than the actual energy required by existing equipment. This indicates the presence of a great deal of friction in the processes and considerable overload capacity to handle the input variations. Much can be done in process and equipment improvement.

Evidence of synergistic effects with the use of combinations of principles indicates the efficacy of some approaches: (1) Automatic presorting followed by separate size reduction; (2) Automatic preshearing followed by a secondary size-reduction operation in the same line; (3) Automatic precrushing followed by subsequent size-reduction operations better suited to ductile material; (4) Multiple-stage size reduction in combinations of parallel and tandem operations (such as precrushing and separation into parallel lines having ductile and nonductile material, followed by further size reduction as required).

Current equipment. A review of current size-reduction equipment indicated that more than two-thirds of this equipment is used primarily on uniform material in industry and is not recommended for direct use on municipal solid waste.

Potential usage, however, does exist for all types of size-reduction equipment. There exist eight general types of size-reduction equipment with variations and potential applications in municipal solid waste size reduction (Table 8).

CURRENT APPLICATIONS, PERFORMANCE, AND COSTS

The survey has shown that current size-reduction equipment, as applied to municipal solid waste, is undergoing growing pains. The trend seems to be toward larger and larger machines.

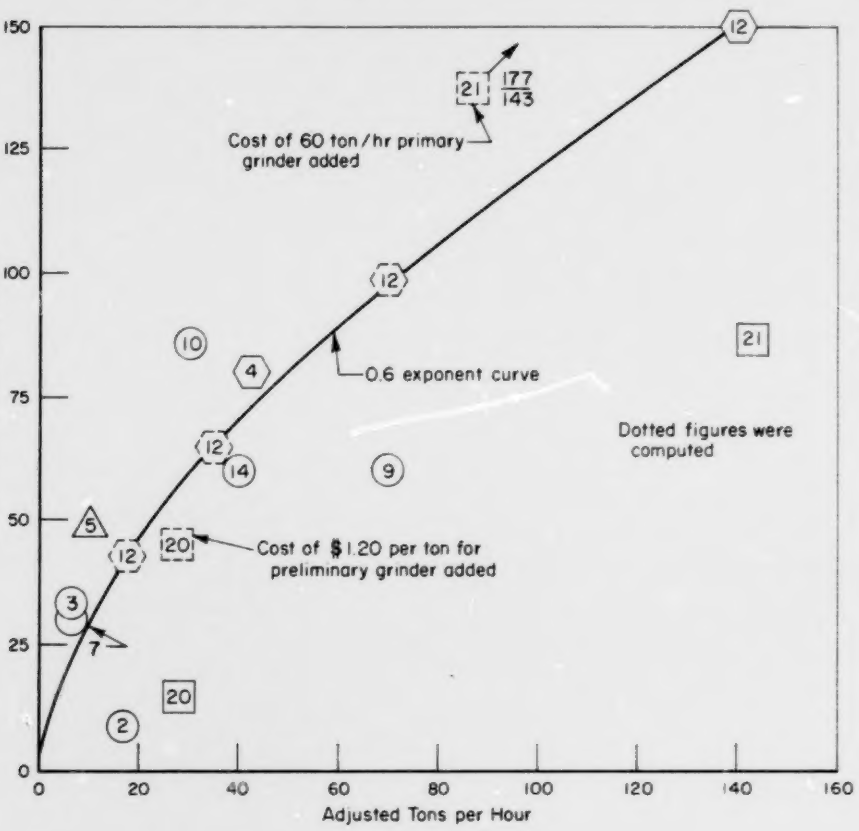

FIGURE 16. *Capital cost versus adjusted capacity.*

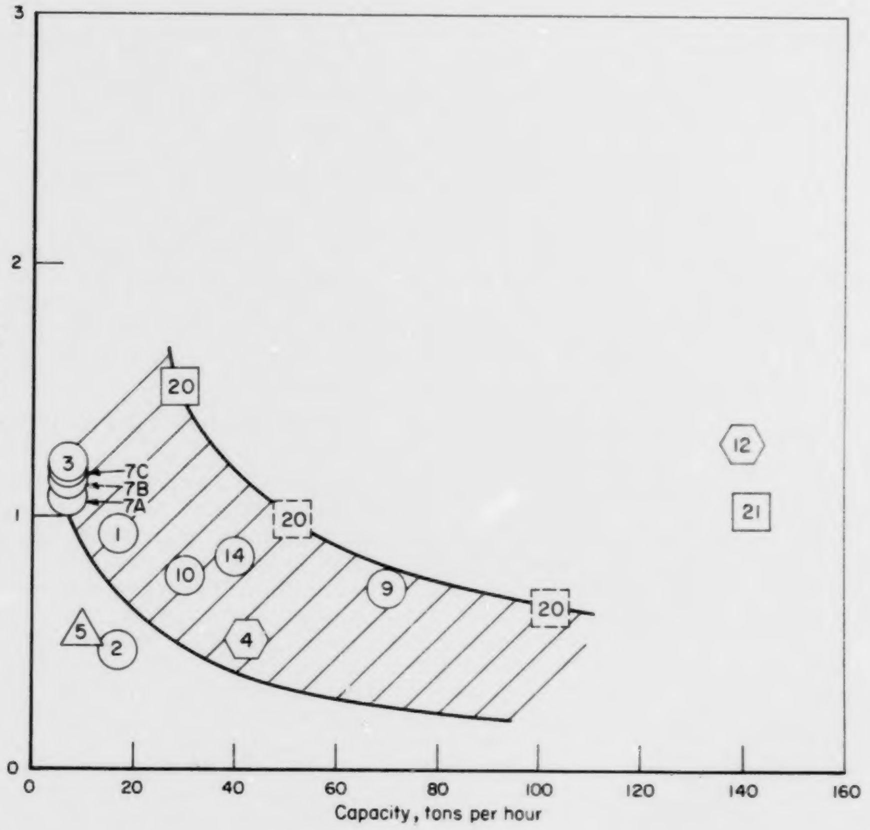

FIGURE 17. *Adjusted maintenance, power, and labor costs of size reduction.*

TABLE 8

CURRENT SIZE-REDUCTION EQUIPMENT AND POTENTIAL APPLICATIONS TO MUNICIPAL SOLID WASTE

Basic types	Variations	Potential application to municipal solid waste
Crushers	Impact	Direct application as a form of hammermill.
	Jaw, roll, and gyrating.	As a primary or parallel operation on brittle or friable material.
Cage disintegrators	Multi-cage or single-cage.	As a parallel operation on brittle or friable material.
Shears	Multi-blade or single-blade.	As a primary operation on wood or ductile materials.
Shredders, cutters, and chippers.	Pierce-and-tear type.	Direct as hammermill with meshing shredding members, or parallel operation on paper and boxboard.
	Cutting type	Parallel on yard waste, paper, boxboard, wood, or plastics.
Rasp mills and drum pulverizers.		Direct on moistened municipal solid waste; also as bulky item sorter for parallel line operations.
Disk mills	Single or multiple disk.	Parallel operation on certain municipal solid waste fractions for special recovery treatment.
Wet pulpers	Single or multiple disk.	Second operation on pulpable material.
Hammermills		Direct application or in tandem with other types.

This trend will probably continue as an expediency to keep up with the fast-growing rate of solid waste generation. Methods to improve efficiency of size-reduction equipment are also being sought, but, as pointed out earlier, this is leading to technical inefficiency. Approaches to greater efficiency have been cited in such combinations as preshearing or precrushing bulky items prior to hammermill action.

The performance and cost data on the wide variety of input material and product size were adjusted to levels corresponding to the size reduction of average municipal solid waste to a nominal 6-in. product. Before adjustment, the power and cost values ranged from 5 hp-hr and $0.46 per ton to 80 hp-hr and $1.77 per ton. After adjustment, the ranges closed from 6 hp-hr and $0.52 per ton to 30 hp-hr and $1.52 per ton, roughly a 3 to 1 decrease in power and cost ratios. The adjusted performance and cost spreads of approximately 4 to 1 are, however, still very high, indicating the need for more closely controlled test conditions or perhaps a better model.

REQUIREMENTS FOR ADDITIONAL DATA

There are obvious gaps in the data coming directly from size-reduction operations on municipal solid waste. Data from the processing of material similar to certain fractions of municipal solid waste, fortunately, have provided usable performance and cost information. This was accomplished by the application of factors derived from the more limited solid waste size-reduction data. Whereas a fair general picture of solid waste size reduction has been obtained, additional data are required in more specific areas. For example, this study has leaned heavily on a single source of data (the Madison, Wisconsin, Demonstration Grant Project) for hammer-wear data and product-size effects. Other demonstration projects will provide data that will permit more information on operations.

Refinements in the collection and processing of data from municipal solid waste size reduction also appear to be desirable. These could be in the nature of a series of closely controlled experiments performed on representative size-reduction units. In these experiments, controlled input and thorough instrumentation should be considered. Standardized containers of selected materials might be one form of controlled input. Using recording instruments, short runs with controlled input could be used to correlate data from the current runs of municipal solid waste. The instru-

TABLE 9

EFFECTS OF NEW EQUIPMENT DESIGNS IN COMBINATION

Design combination	Possible effects	
	Advantages	Disadvantages
Bottle breaker on municipal solid waste conveyor leading to hammermill.	Friable material reduced by lower wearing-rate members.	More complicated conveyor.
Wet pulpers, single- or multiple-abrasive-disk radial axis with hammermill.	Finer product better suited to some separation and recovery operations.	Higher investment.
Lump-breaker feed on refuse cutting machine.	Crushing action tends to homogenize the refuse.	More complicated conveyor.
Axial feed on preliminary disintegrating machine.	Homogenizing and preliminary size reduction.	
Drum pulverizer feeding hammermill.	Fine material can bypass the final stages.	Higher investment.
Ultrasonic apparatus after primary separation operation.	Minimum wear.	Material limitation.
Screw driers on wet pulpers.	Minimum cost.	Input material limited.
Individually removable hammers on hammermill.	Minimum downtime, staggered hammers, reduced vibration.	Higher investment.
Oblique cornered hammers on hammermill.	Greater shearing action, more wearing volume, higher impact.	More vulnerable to damage.
Shear-type feed of hammermill.	Less slugging.	Higher investment.
Crushing-type hammermill feed.	Less slugging, less wear (especially if crushed friables bypass hammers).	Higher investment.
Shredding action with hammermill.	Closer grip on material during fracture precludes grate plugging.	More vulnerability.
Combination of shear, crush, and shred.	Homogenization plus semi-primary size reduction, minimum wear.	Higher investment.

mentation could be so complete as to record such data as motor loads, speeds, strains, temperatures, and noise level. Part wear could even be monitored by scintillator readings of tracer elements worn from specially prepared wearing members.

The data that should be obtained in a controlled test are summarized in the following list of possible requirements:

(1) Motor current
(2) Voltage
(3) Kilowatts
(4) Speed
(5) Bearing load (strain gage)
(6) Temperatures
  (a) Bearing
  (b) Product
(7) Noise level
(8) Wear monitoring by tracer element check
(9) Standard test materials
  (a) Unsorted, packaged in oil drums
  (b) Precrushed, in boxes along with flattened oil drums
(c) Presheared, in smaller cans.

Instrumentation to record the above-listed data would probably be too costly and complex for continuous use on one installation, so a portable package unit is recommended for spot checking several municipal solid waste size-reduction installations.

NEW EQUIPMENT DESIGNS

Summaries of new equipment designs as applied to municipal solid waste are slanted mainly toward possible synergistic effects, although some antagonistic effects result and are pointed out.

The patents and Battelle-generated concepts discussed in Appendix B disclose various features having possible application to municipal solid waste size reduction. These designs and some of the more likely combinations along with possible advantages and disadvantages are listed (Table 9).

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V. Separation

FOLLOWING SIZE REDUCTION, separation is sequentially the second critical step in the recovery and utilization of mixed municipal solid waste.

Due to the heterogeneity of typical solid waste and the diversity of recovery operations which can be conceived, separation is a second important step in the recovery and utilization of solid waste. The efficiency with which separation is effected and the degree to which the desirable materials can be segregated are significant factors contributing to cost and marketability of recovered products. Consequently, significant effort was devoted to the collection of technical data for equipment and processes that could be used in the separation of solid waste.

As of 1968, the most widely employed means for separating solid waste is handpicking and sorting from conveyors. Handsorting is employed, almost without exception, at nearly all U.S. and European compost plants, and at some municipal incinerators, to remove such items as clean newsprint and cardboard, rags, metals, glass, and plastic (Figure 18). These materials are removed for salvage purposes and, in the case of composting, to upgrade the quality of the final product. Handsorting is unsatisfactory for large-scale recovery and utilization for several reasons including: (1) low salvage prices that limit the economic attractiveness of such operations; (2) limited degree of separation that can be effected since a nominal size work force can be concerned only with removing more bulky pieces; and (3) human fallibility. It

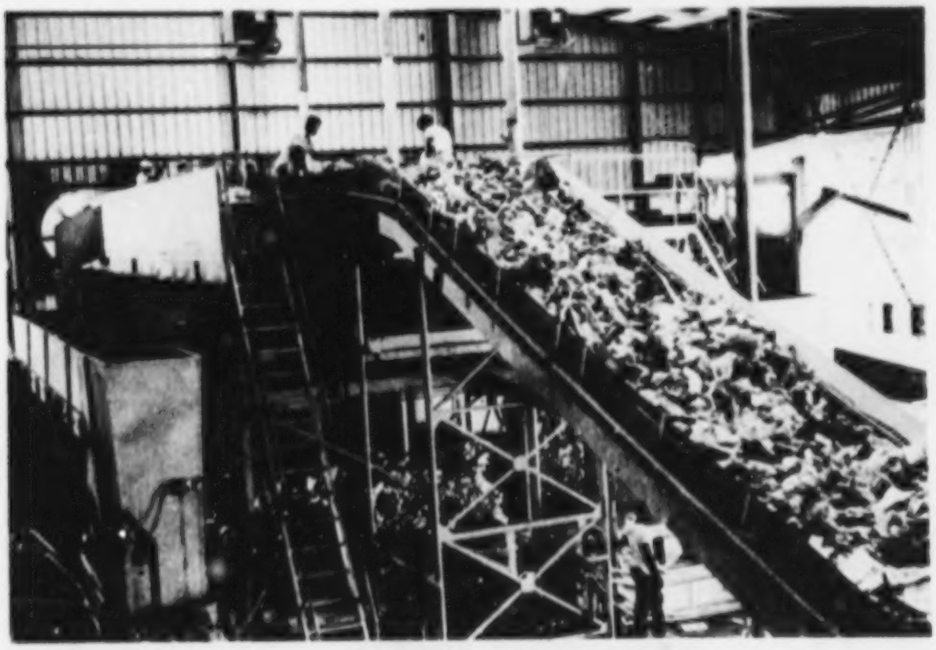

FIGURE 18. *Handsorting at Lone Star Organics, Inc., compost plant, Houston, Texas.*

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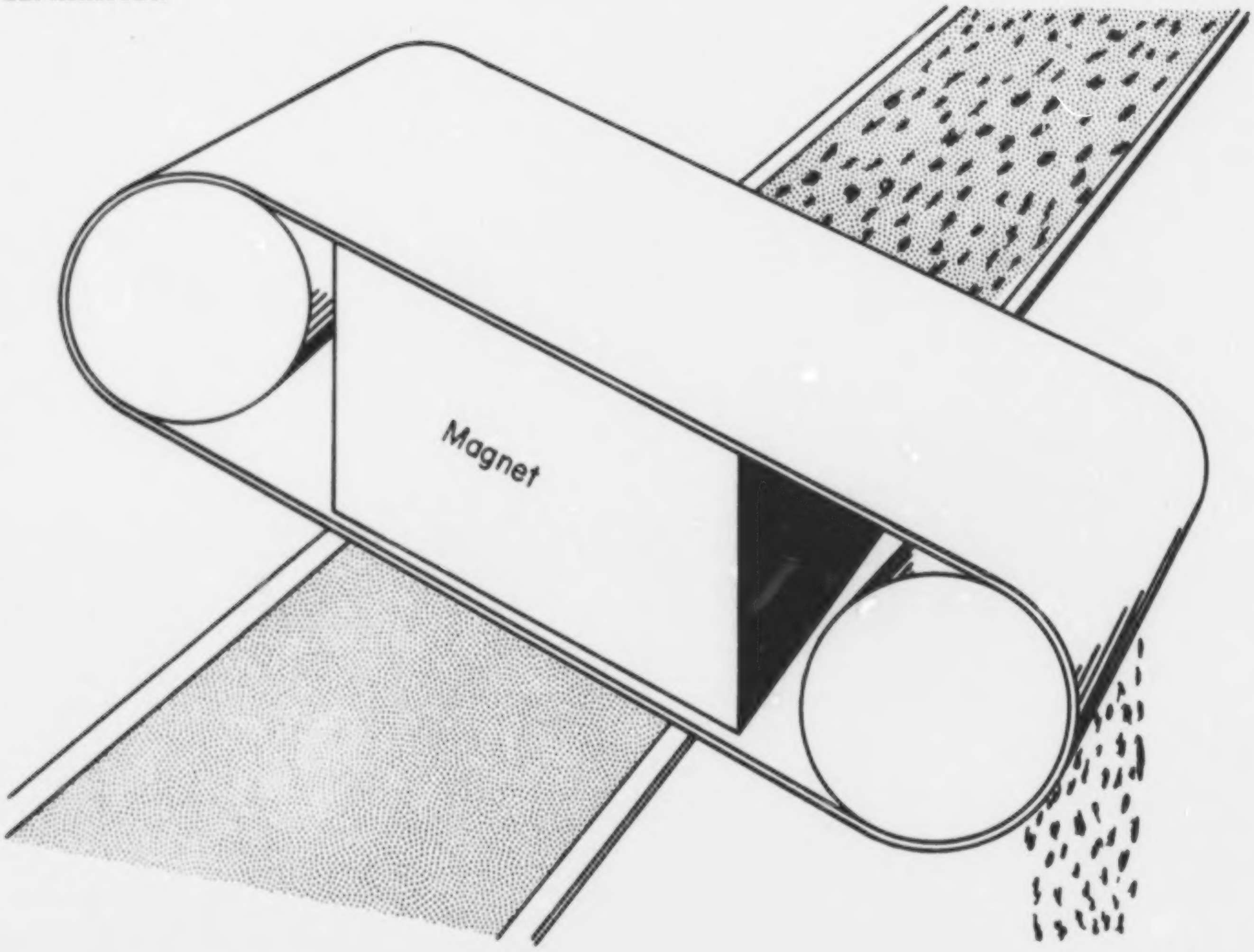

FIGURE 19. *Eriez suspended-type permanent magnetic separator.*

has been reported that approximately ½ to ¾ ton of newsprint and cardboard can be handpicked from mixed waste by one man in an hour.[11] This corresponds to 1⅓- to 2-man hr per ton. Separation costs, therefore, ranges on the order of $3.50 to $5.00 per ton assuming low cost labor.

The need was recognized for a variety of improved separation techniques owing to the extremely limited existing applications of more advanced technology to solid waste processing.

The entire field of industrial separation technology was surveyed in detail for potentially adaptable techniques and related performance characteristics and costs. As indicated below, very few of the more sophisticated separation techniques have been applied to solid waste processing, and the historical experience of these applications is extremely limited. Therefore, much of the cost and performance data available relates to industrial applications significantly different from solid waste processing and must be employed and interpreted with extreme care. These data should not be used for design purposes, but rather should be employed to indicate the general types of separation possible, general feed requirements, and order-of-magnitude costs. This type of information is essential in making preliminary judgments as to potentially attractive process combinations for investigation on both pilot and demonstration scale. Several such combinations are discussed in a later section.

As indicated, this study has attempted to cover a largely uncharted domain of technology. Two approaches were possible. One would have been to decide *a priori* what components and mixtures were desirable to separate and then to limit the investigation to a search for equipment which would effect the separation. Alternatively one could ask the question, what can be separated using existing and potential equipment designs. The former approach was not suitable to the task at hand, since the decision as to what one would like to separate depends to a large extent upon what can be separated, what degree of separation can be effected, and other undefined factors relating to markets, and the processing and recovery of by-products. Consequently the second approach was elected; and the general overall task was to determine what types of separations are, or might be, possible using existing technology, with or without suitable modifications. This information is presented below to the extent that it is available.

Separation techniques are designed to detect and to operate selectively on differences in various properties of the materials being separated. Primary properties employed in the separation techniques investigated in this study

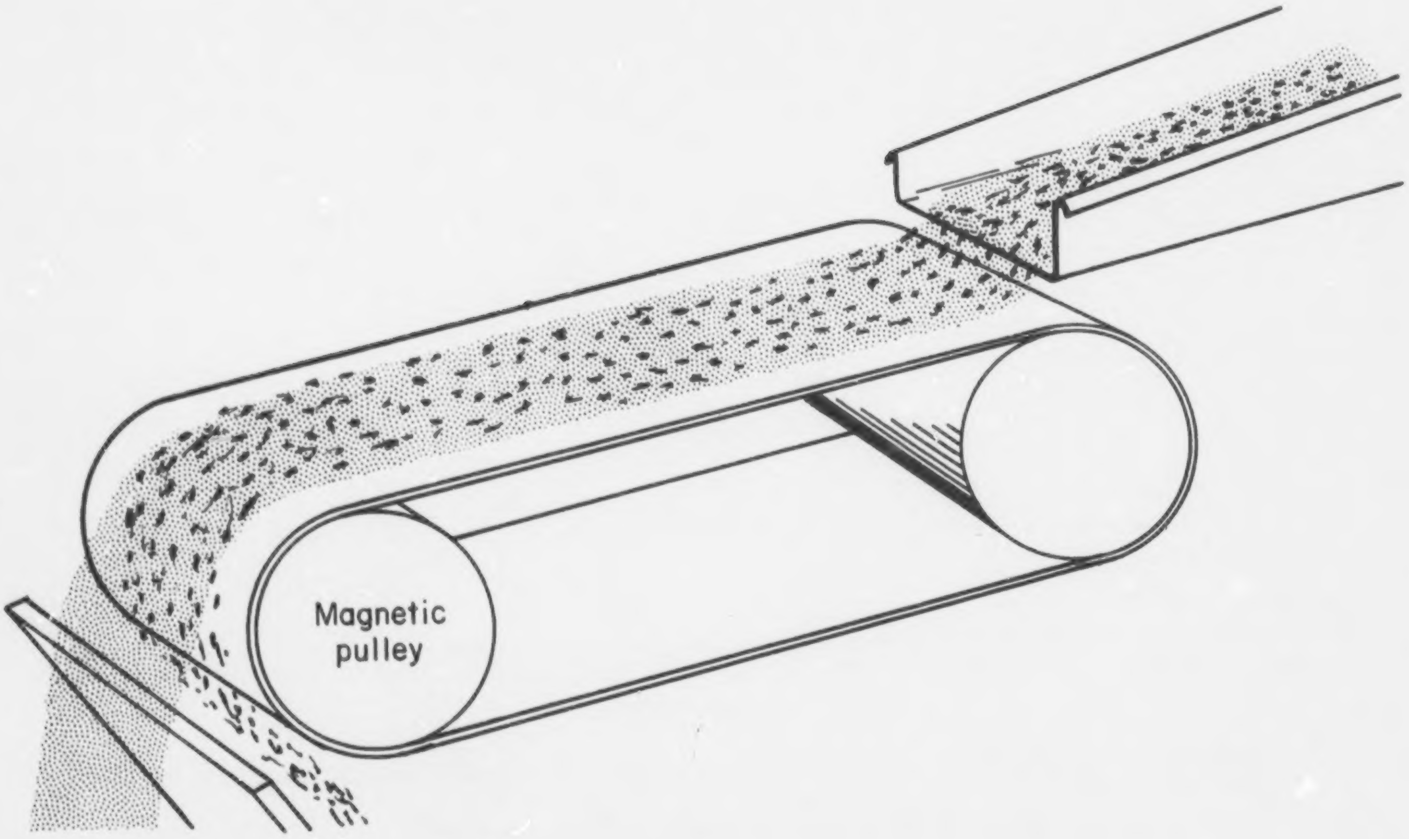

FIGURE 20. *Eriez pulley-type permanent magnetic separator.*

include magnetic properties, particle size, specific gravity, and light reflectance properties of the surfaces. The primary obstacle in the application of these techniques to the separation and recovery of solid waste is that the components which one might wish to separate are generally not sufficiently unique in any single property such that the separation is rendered straightforward. Consequently, the best one can imagine is a combination of processes and somewhat less than 100 percent separation.

Technical information and available data on specific processes and separation techniques are outlined below. Generally speaking, there is almost a universal lack of data related to the mechanical separation of solid waste. Most of the performance and cost statements in this report are based on qualitative extrapolations of data for specialized industrial applications. Experimental data need to be collected for nearly all applications discussed to determine interrelationships among such properties as particle size and distribution in the mixed feed, separation efficiency, capacity, moisture content, and material type.

Three general sources of information were employed in this phase of the study. These are existing plants and operations, equipment manufacturers, and patent literature. As indicated below, several potentially promising separation techniques are available; but additional experimental work is required to establish performance criteria and cost relationships suitable for design purposes.

UNIT PROCESSES FOR SOLID WASTE SEPARATION

MAGNETIC SEPARATION

The removal of ferrous materials from heterogeneous industrial mixtures and from municipal solid waste is practiced quite widely. Prevalent industrial applications include minerals beneficiation, the recovery of scrap in metal fabrication plants, and automobile salvage operations. Compost plants in Houston, Texas; Gainesville, Florida; and Johnson City, Tennessee; and other municipal incinerators in Atlanta, Georgia; Chicago, Illinois; and other localities use magnetic separators to remove tin cans. Tin cans are removed for salvage and, at the compost plants, to upgrade the quality of the final product.

In general, two types of separators are adaptable to the removal of ferrous materials from mixed refuse and are used extensively in solid waste processing plants (i.e., compost plants and municipal incinerators) which are removing tin cans from mixed refuse. These may be broadly classed as suspended-type and pulley-type separators (Figures 19 and 20). Suspended-type separators are used to

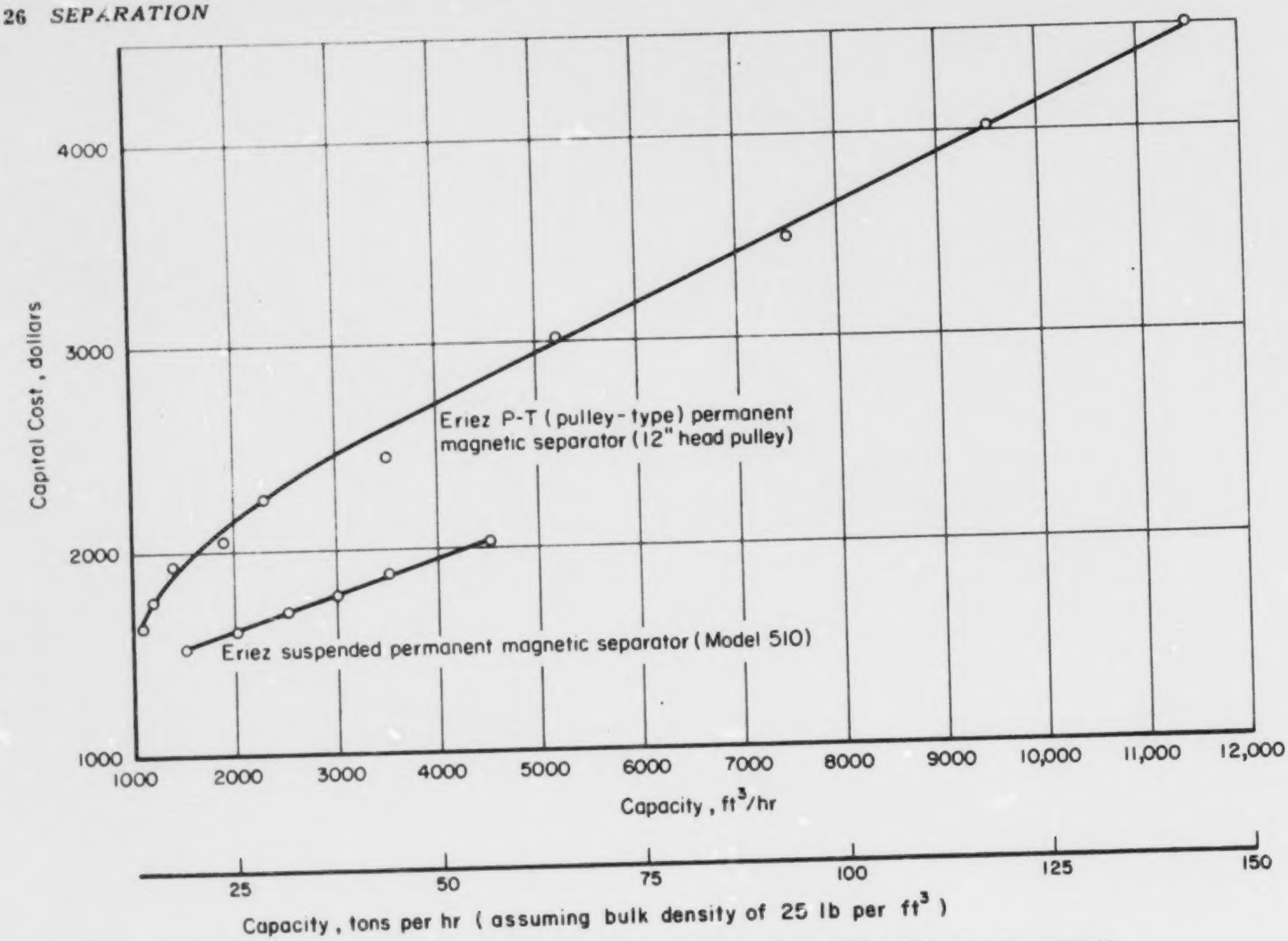

FIGURE 21. *Capital cost of magnetic separators. (Data supplied by Eriez Manufacturing Company.)*

make a "first cut" to remove ferrous materials from refuse which may or may not have been subjected to size reduction. The pulley-type separators are employed as a second-stage cleanup to remove ferrous materials after removal by a suspended-type separator and processing through a hammerhill.

Efficient magnetic separation is affected mostly by the degree of size reduction provided and the extent to which ferrous materials are physically liberated from other types of materials. Hammermilling, and perhaps even crushing, of raw waste is considered to be satisfactory preparation for efficient magnetic separation of ferrous materials from solid waste. The particle size in the feed material to the magnetic separator is not critical, since existing equipment can accommodate nearly all ferrous objects ranging from large tin cans on down. The occasional large items such as appliances need to be reduced in size to pieces about 8 in. or smaller. In any event, the primary requisite for efficient magnetic separation is that the materials be physically freed from one another. Magnetic separation is not likely to be affected by, or to have major effects upon, other upstream or downstream separations, except perhaps in the sense that inefficient removal of ferrous material may result in an unexpected contaminant or component to be reckoned with at later processing or recovery stages.

Equipment employed in the removal of tin cans from solid waste are adaptations of equipment designed primarily for large industrial operations such as the automobile macerators and salvagers. Consequently, the capacities of existing equipment, ranging from 25 to 100 tons-per-hr, are considerably higher than required in solid waste processing plants where the ferrous content of the throughput is relatively small. For example, ferrous throughput rates for various nominal plant sizes and ferrous content are as follows (Table 10).

TABLE 10

FERROUS THROUGHPUT RATES AS A FUNCTION OF CONTENT AND PLANT SIZE

Total solid waste throughput		Ferrous content	Ferrous throughput
(tons/10-hr day)	(tons/hr)	(percent)	(tons/hr)
150	15	5	0. 75
		6	0. 90
		7	1. 05
		8	1. 20
300	30	5	1. 50
		6	1. 80
		7	2. 10
		8	2. 40

Data provided by Eriez Manufacturing Company, a large supplier of magnetic separators, indicating capital cost as a function of size and capacities of the two main types of

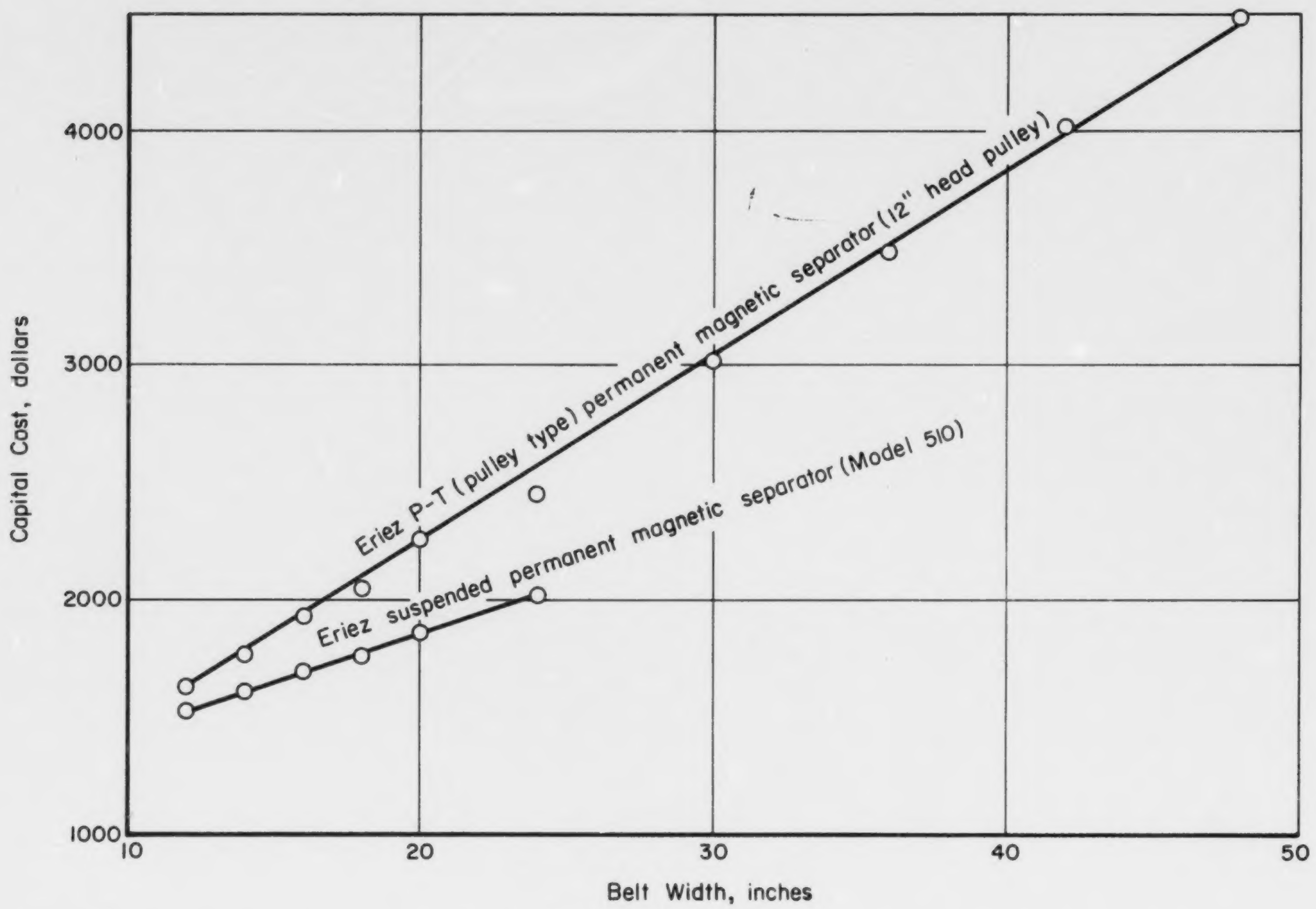

FIGURE 22. *Capital cost of magnetic separators. (Data supplied by Eriez Manufacturing Company.)*

magnetic separators are provided (Figures 21 and 22). Equipment is rated by the manufacturer in terms of cu ft per hr; and the tonnage capacities given are based upon the bulk density of the ferrous material as 25 lb/cu ft. Operating costs for magnetic separators are minimal and result primarily from power consumption. Small magnetic separators, more than adequate for use in solid waste recovery, require at most about 1 hp, and so power costs for magnetic separation are expected to be an insignificant fraction of total power consumption in a solid waste recovery plant. Consequently, the major cost of magnetic separation is the cost of equipment, especially the auxiliary equipment for handling influent and effluent streams. Cost data for tin can recovery facilities discussed in a later section indicate that the major cost item is not the magnetic separator, but, rather, the auxiliary facilities.[12] The total cost of a can recovery facility at an 800-ton/day incinerator was estimated at $400,000, with the major fraction of the capital cost being attributable to site preparation, structures, and auxiliary equipment such as a shredder, conveyors, and railroad siding. Similarly only a fraction of the estimated operating costs are attributable to the magnetic separation process. In fact, less than 25 percent of the total cost for all equipment was attributable to power and maintenance. The remaining 75 percent resulted from labor (system operators and inspectors). Total cost of can recovery including amortization and operating cost was estimated to be $13.60 per ton recovered.

The above analysis of magnetic separator costs indicates something which one must keep in mind when interpreting the various unit process costs quoted throughout this report. The point is that the unit process itself may constitute only a small fraction of the cost required to put this process in operation. As in the above example, the major cost item may be the supporting and auxiliary materials handling equipment needed to synthesize a complete system. A similar trend is noted in a later section on composting where it is seen that actual digester costs are only about 25 to 40 percent of the total capital investment required.

In addition to the standard magnetic separation equipment discussed above, one additional rather unique application is worthy of mention. The Los Angeles By-Products Company operates several machines at various landfills in the San Francisco area which remove tin cans from loads of refuse dumped at the landfill sites. The salvaged products eventually find their way to the copper smelters. Current design as well as operational details of these machines, including costs, are considered to be proprietary information by Los Angeles By-Products Company[13] A patent search led to the discovery of a patent relating to an early design of this machine.[14]

EDDY-CURRENT SEPARATION

The separation of nonmagnetic, conductive materials (copper, aluminum, zinc) in solid waste based upon eddy-current phenomena has been proposed on several occasions. However, limited experimental studies conducted to date have indicated substantial problems in the application of this phenomena not only to the separation of materials from municipal solid waste, but also to the segregation of much less heterogeneous industrial waste. Eriez Manufacturing Company, for example, has investigated these applications rather extensively and has been quite cooperative in providing information on its research in this area.[15] The following discussion is based largely upon information provided by Eriez.

Since the principles of eddy-current separation are not well documented in the solid waste literature, they are outlined briefly below.

When an electric current is passed through a coil surrounding a core made of a conducting material, a magnetic flux develops (Figure 23). By varying the current, one may cause the magnetic flux to change. This changing magnetic flux is the key to eddy-current phenomena. It should be noted that the arrangement shown is only one means of producing a changing flux and is selected for illustration because the arrangement simplifies explanation of the phenomena under consideration. Another technique for creating a changing flux, more suitable to the concept of an eddy-current separator, is discussed later. As indicated, the changing magnetic flux is the key to eddy-current phenemona. This is true because when a magnetic field in a conducting medium changes with time, an electromotive force is generated in the plane of the medium which is perpendicular to the direction in which the flux is changing. As a result of the electromotive force, eddy currents develop within the material. Associated with these eddy currents is an eddy-current flux which is opposite in direction to the initially imposed magnetic flux.

The eddy-current flux may be employed to effect a separation (Figure 24). As previously mentioned, the eddy-current flux always opposes the flux that produced it. These two opposing magnetic fields create a repel-

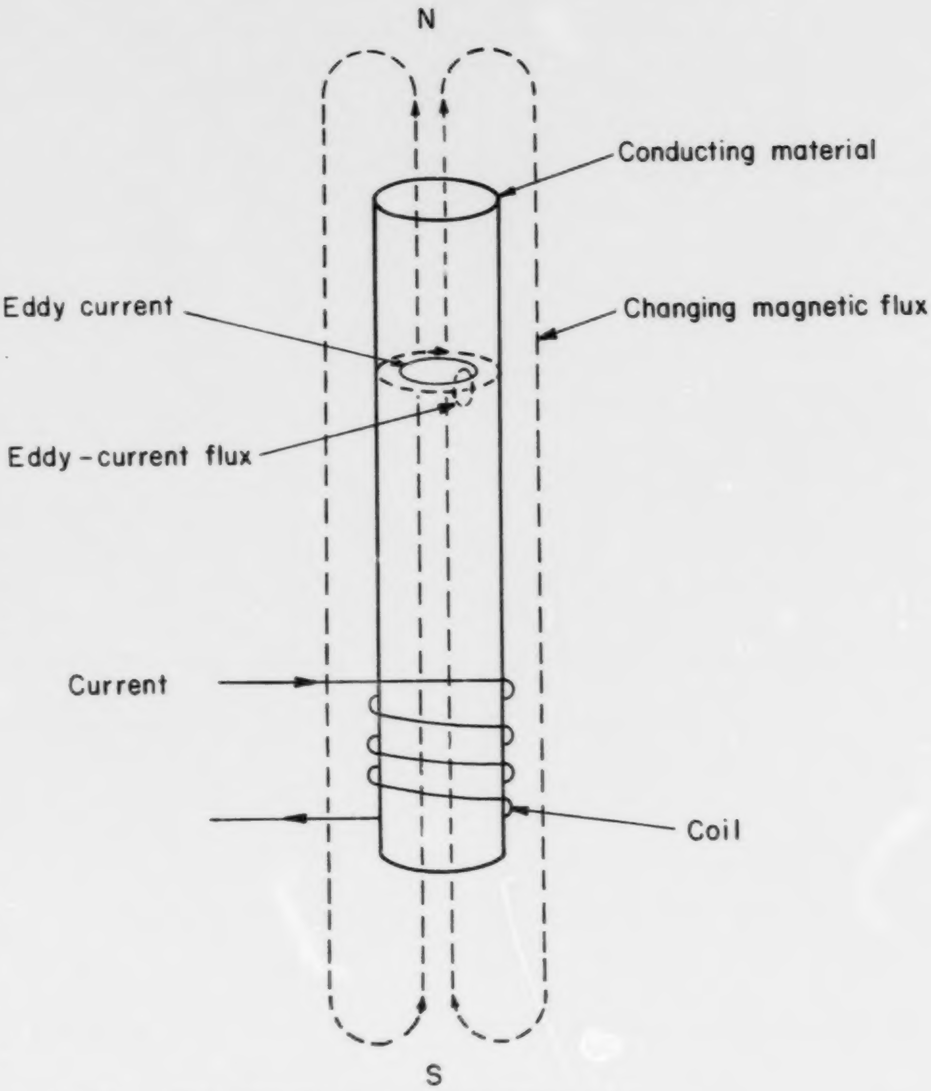

FIGURE 23. *Principles of eddy-current phenomena.*

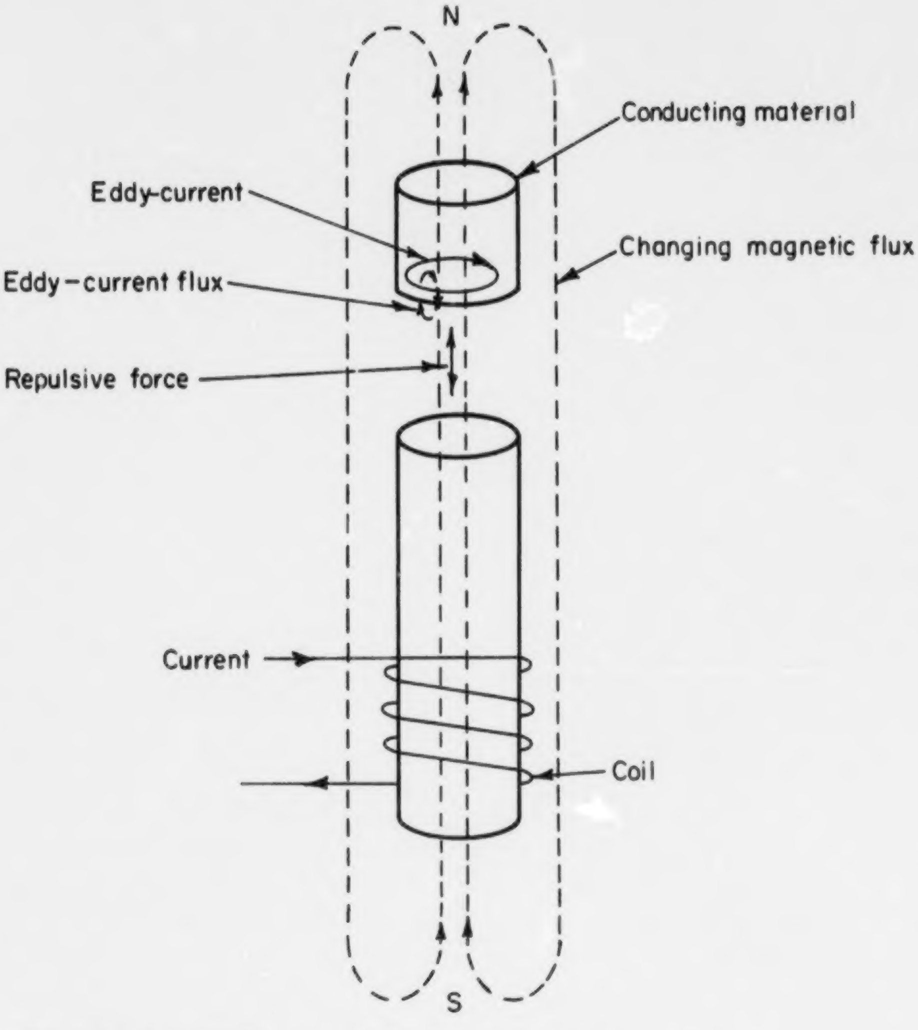

FIGURE 24. *Application of eddy-current phenomena.*

ling force, and if the core consists of two parts, separation will occur.

In principle, the phenomena discussed above could be employed to separate various nonmagnetic conductive materials since the magnitude of the repulsive force depends in part upon characteristics of the material such as its resistivity and permeability. Other factors, unrelated to material characteristics, are the magnitude and the rate of change of flux density. One attempt by Eriez to apply these principles involved the use of a magnetic pulley (Figure 25). In this case, a drum is equipped with a series of magnets installed around its interior circumference which in turn cause a magnetic field to develop outside the drum or pulley; and by rotating the pulley, a constantly changing flux is produced. When a nonmagnetic conductive material is placed in this changing field, eddy currents develop in the material and a repulsive force is generated. If this force is sufficiently strong, it will deflect the material and effect a separation.

In addition to the pulley arrangement, other configurations have been investigated in an effort to develop a suitable eddy-current separator. Eriez has reported serious limitations with all techniques studied to date. The basic difficulty is that the magnitude of the repulsive force generated depends largely upon the geometry of the materials to be separated. The size, shape, and surface irregularities play a key role. Since the technique has not been perfected, an optimum particle size cannot be defined. It should be noted, however, that in the Eriez experimental work, ½-in.-diameter disks, ⅛-in. thick, were used. In genuine waste mixtures, particles exhibit a wide degree of variation in size, shape, and surface irregularities. A piece of aluminum, for example, may be subjected to the same repulsive force as a piece of copper due to differences in particle geometry even though significant differences exist in material characteristics. Consequently, meaningful separations do not result when using a typical waste feed. To date a suitable technique for overcoming these limitations has not been discovered, and prospects that one will be discovered in the near future are not great. At present, eddy-current separation does not constitute a technically promising method of separating the various nonmagnetic, conductive materials in municipal solid waste.

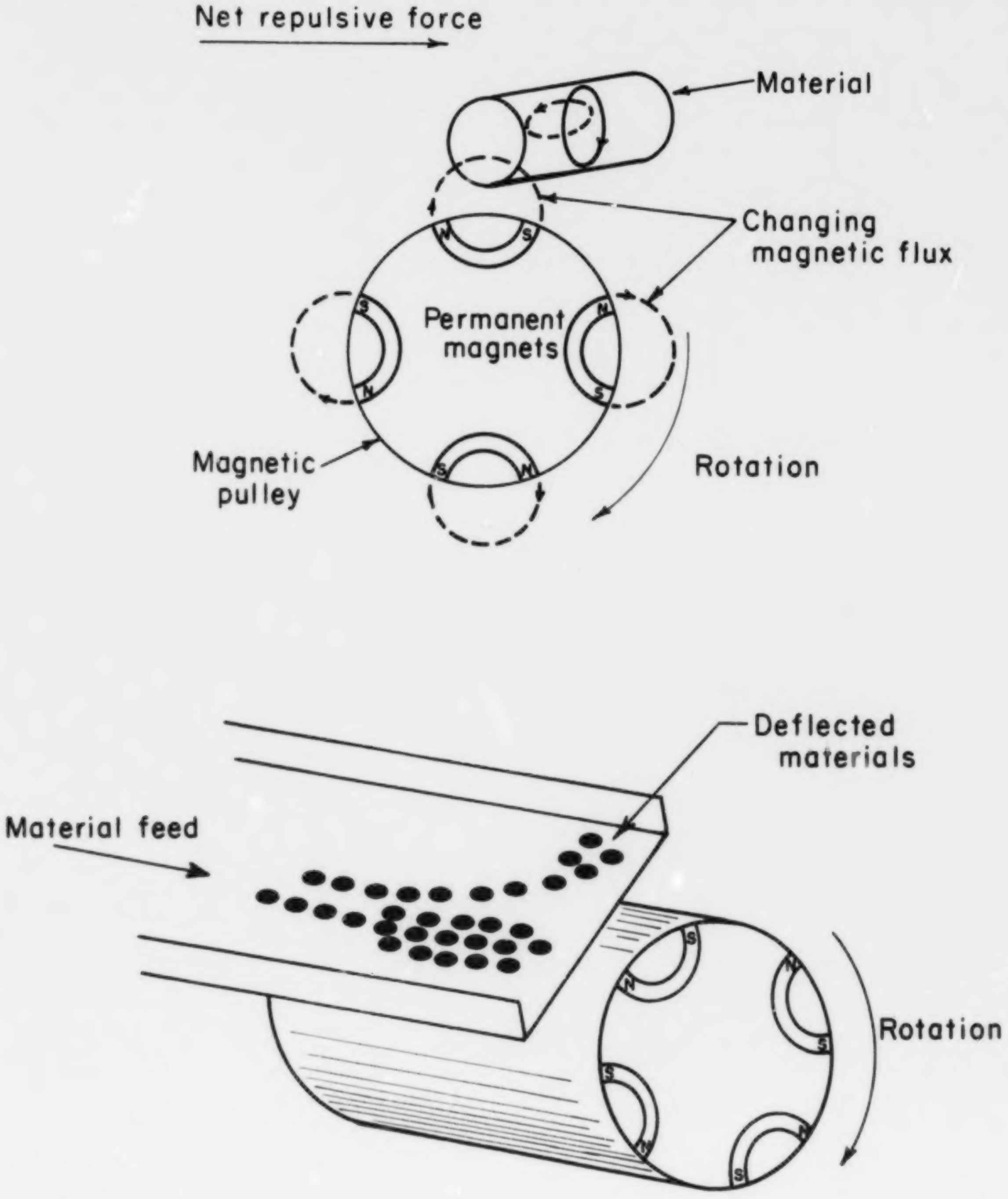
Net repulsive force
Material
Changing magnetic flux
Permanent magnets
Magnetic pulley
Rotation
Deflected materials
Material feed
Rotation

FIGURE 25. *Concept of pulley-type eddy-current separator.*

TABLE 11

VARYING DEGREES OF SIZE REDUCTION FOR GLASS, TIN CANS, AND WOOD WASTE *

Glass		Tin cans		Wood	
Size range (in.)	Material occurring in stated size range (percent)	Size range (in.)	Material occurring in stated size range (percent)	Size range (in.)	Material occurring in stated size range (percent)
>¼, <½	6	>3	15. 7	1½ to 8 x 1½ x 1.	40
>⅛, <¼	9	>2, <3	30. 5	0 to 1½	60
>1/16, <⅛	14	<2	58. 8		
>1/32, <1/16	20. 5				
<1/32	50. 5				

* From Stirrup, F. L. Public cleansing refuse disposal. Oxford, England, Pergamon Press, 1965. p. 68.

SIZE CLASSIFICATION

Vibrating screens. Screening is a technique for separating materials based upon particle size and involves the separation of a mixture of various size particles into two fractions, or more if multiple deck screens are used, each of which is more uniform in particle size than is the original mixture. Screening may be wet or dry. Dry screening implies the treatment of a material containing a natural amount of moisture or a material that has been dried before screening; whereas wet screening refers to an operation in which water is added to the material being treated for the purpose of washing the fine material through the screen. Another application of wet screening is the dewatering of slurries containing relatively hard solids which will not blind (clog) the screen.

Within the context of solid waste processing, it appears that only dry screening has major potential application. The small quantity of fine materials (fines) in solid waste would not merit wet screening because of the auxiliary problems of water handling, material drying, and their tendency to become quite soft in an aqueous environment, thus blinding the screen.

As is the case for many separation processes discussed in this report, the selection of screening equipment requires empirical studies to determine the effect of the several variables. The critical variables are so interrelated that no satisfactory analytical method of correlating them has been developed. Therefore, no specific recommendations can be made as to type of screen material to be selected, or capacity and efficiency to be obtained. Manufacturers suggest that processors submit samples for testing prior to selection of equipment. Critical factors include particle-size distribution, density, and undefined interactions among particle size, shape, and moisture content. All available published data on screen capacities relate to minerals-oriented processes, and this experience is not directly applicable to solid waste processing.

The only reported experience with the use of screens in the processing of solid waste is at two compost plants; one in Houston, Texas, and the other in Altoona, Pennsylvania, where screens are used to size the compost before a stoning operation to remove glass as described in a later section. Performance data from these applications were not available at the time of this study.

The sizing of waste product streams for further separation and processing appears to be one of two major potential applications for screening in the recovery and utilization of solid waste. The other relates to a possible, but as yet quantitatively undefined, synergistic effect in conjunction with size reduction. Specifically it seems reasonable to expect that during size reduction, brittle materials such as glass, metals, and thermosetting plastics might end up in smaller pieces due to their relatively lower resistance to impact than materials such as paper and food wastes. If this phenomena does occur to an appreciable extent, a basis would exist for making a separation in a two-stage size-reduction screening operation. A small amount of published data is available which would cause one to expect these effects.[16] The results of studies conducted in England indicate varying degrees of size reduction for glass, tin cans, and wood (Table 11).

Costs of screening are related almost entirely to equipment costs and only in a small way to operating costs which are, in turn, dictated principally by power consumption. Capital costs of screening equipment are generally given in terms of square feet of screen area. Required area is, in turn, determined by screening rates.

A fair amount of data is available for estimating screen sizes required for conventional minerals applications. However, as previously indicated, applications to solid waste processing are extremely limited and performance data are not available. Nevertheless, the data on minerals separation can be employed to determine approximate performance characteristics for other potential solid waste processing.

Denver Equipment Company has supplied a technique for estimating screen size requirements (Table 12). Values are given for various factors related to key design variables. Note that Factor A, which is directly proportional to screen openings and which is also related to material type, is provided only for conventional minerals processing. Depending on the type of material, Factor A ranges between a low of 1.08 to a maximum of 4.90. Thus for materials listed, required screen area could vary by a factor of about five. This range of variation would be expected to be even more pronounced, perhaps as great as a factor of ten, for application to solid waste. Thus the procedure given is satisfactory only for determining order-of-magnitude screen area requirements. It also serves, however, to indicate the type of experimental studies required, the vari-

TABLE 12

CAPACITY OF VIBRATING SCREENS FOR MINERALS APPLICATIONS*

Factor A

Mineral (inches)	Size (in.) and mesh size of clear square opening									
	.0116 48	.0164 35	.0232 28	.0328 20	.046 14	.065 10	.093 8	1/8	.131 6	.185 4
Sand	.143	.183	.226	.282	.36	.45	.57	.69	.73	.90
Stone dust	.120	.158	.188	.235	.30	.375	.475	.58	.595	.75
Coal dust	.091	.115	.142	.178	.226	.284	.36	.43	.45	.57

Mineral (in.)	Size of clear square opening (in.)													
	1/4	3/8	1/2	5/8	3/4	7/8	1	1 1/4	1 1/2	2	2 1/2	3	4	5
													(Use only in single-deck screens)	
Gravel	1.08	1.40	1.68	1.94	2.16	2.36	2.56	2.90	3.20	3.70	4.05	4.30	4.65	4.90
Crushed stone	.88	1.19	1.40	1.60	1.80	1.98	2.12	2.40	2.68	3.10	3.38	3.60	3.86	4.07
Coal	.68	.88	1.01	1.21	1.38	1.48	1.60	1.83	2.00	2.31	2.53	2.69	2.91	3.06

Factor B—oversize

Determine or estimate percentage of oversize in feed to screen and use proper factor as given below. For example, if screen has 1-in. openings and 60 percent of feed to screen will go thru 1-in. openings, there is 40 percent of oversize and factor 0.95 would apply. Other percentages accordingly.

Amount of oversize (percent)	Factor
10	1.06
20	1.01
30	0.98
40	0.95
50	0.90
60	0.86
70	0.80
80	0.70
85	0.64
90	0.56
92	0.50
94	0.44
96	0.35
98	0.20
100	0.00

Factor C—efficiency

Slight inaccuracies are seldom objectionable in screening aggregate and perfect separation (100 percent efficiency) is not consistent with economy. For finished products, 98 percent efficiency is the extreme practicable limit and 94 percent is usually satisfactory. Sixty to seventy-five percent efficiency is usually acceptable for scalping purposes.

Desired efficiency (percent)	Factor
60	2.70
70	1.70
75	1.55
80	1.40
85	1.25
90	1.10
92	1.05
94	1.00
96	0.95
98	0.90

Factor D—undersize

Consider this factor carefully where sand or fine rock is present in feed. For example, if screen has 1/2-in. square openings and a large percentage of the feed is 1/4 in. or less in size, such as sand or dust, determine percentage and use proper factor given below.

Amount of feed less than 1/2 the size of opening (percent)	Factor
10	0.55
20	0.70
30	0.80
40	1.00
50	1.20
60	1.40
70	1.80
80	2.20
90	3.00
100	

Factor E

If material is dry, use factor 1.00. If there is water in material or if water is sprayed on screen, use proper factor given below. Wet screening means the use of about 6 to 10 gpm of water per cu yd of material per hr.

Wet screening	
Size of opening (in.)	Factor
1/32	1.25
1/16	3.00
1/8	3.50
1/4	3.50
1/2	3.00
5/8	2.50
3/4	1.75
1	1.25

Wet screening below 20 mesh not recommended.

Factor F

For single-deck screen, use factor 1.00. For a multiple-deck screen, be sure to use proper factor for each deck.

Deck	Factor
Top	1.00
Second	0.90
Third	0.75

*Source: Denver Equipment Company.

(1) To obtain capacity in tons per hr passing through screen cloth, multiply area of screen cloth by factors A, B, C, D, E, and F.
(2) To obtain total capacity of screen, add percentage of oversize to result of computation (1).
(3) To determine size of screen, obtain screen-cloth area needed by dividing capacity in tph less oversize in tph by factors A, B, C, D, E, and F.

$CP = Area \times (A \times B \times C \times D \times E \times F)$ in which: A, B, C, D, E, F are factors given above

$TC = CP + Oversize$

$$Area = \frac{TC - Oversize}{A \times B \times C \times D \times E \times F}$$

CP = Capacity passing through screen (tph)
TC = Total capacity of screen (tph)
Area = Screen surface (ft²)

ables that need to be monitored to gather data to determine screen capacity requirements for given applications, and the relative effects of the key properties.

Data were provided by two manufacturers* indicating screen capacities for selected industrial applications (Figures 26 and 27). It is seen that throughputs range from about 1 to 8 tons/hr per sq ft of screen. Nominal particles size range for dry screening is ⅛ to 3 in. Still needed are data that concern the relationships between particle size, capacity, and efficiency of separation for processing solid waste and various component and by-product streams.

As indicated, the primary reason for concern with screen capacities at this stage is to provide a means for estimating cost. Cost data were provided by the two manufacturers for single and double deck screens (Figures 28 and 29).

Spiral classifiers. Spiral classification is a minerals beneficiation technique developed specifically for wet sizing high-density materials. Most common applications relate to removing fine solids from coarse solids of approximately the same specific gravity. By controlling design and operating conditions, cuts can be made on mixed materials containing particles in the size range 200 mesh to ⅛ in. In addition, the basic equipment is also adaptable to separation of light materials from heavy materials of approximately the same size.

The spiral classifier consists of an inclined tank containing one or more inclined revolving spirals. A slurry containing the materials to be separated is fed into the lower end of the unit where it collects in a pool. The

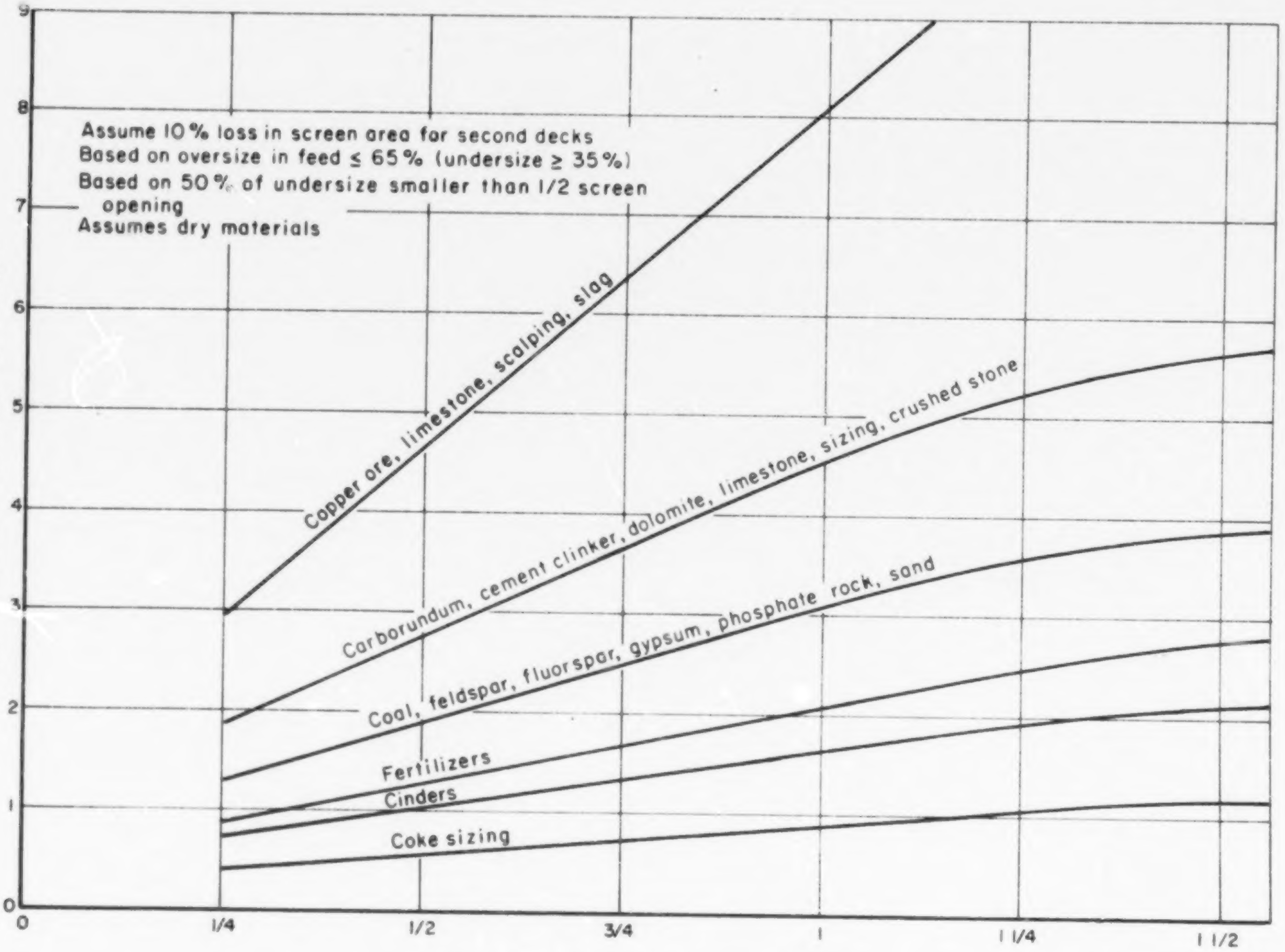

FIGURE 26. *Capacity of Denver vibrating screens. (Data supplied by Denver Equipment Company.)*

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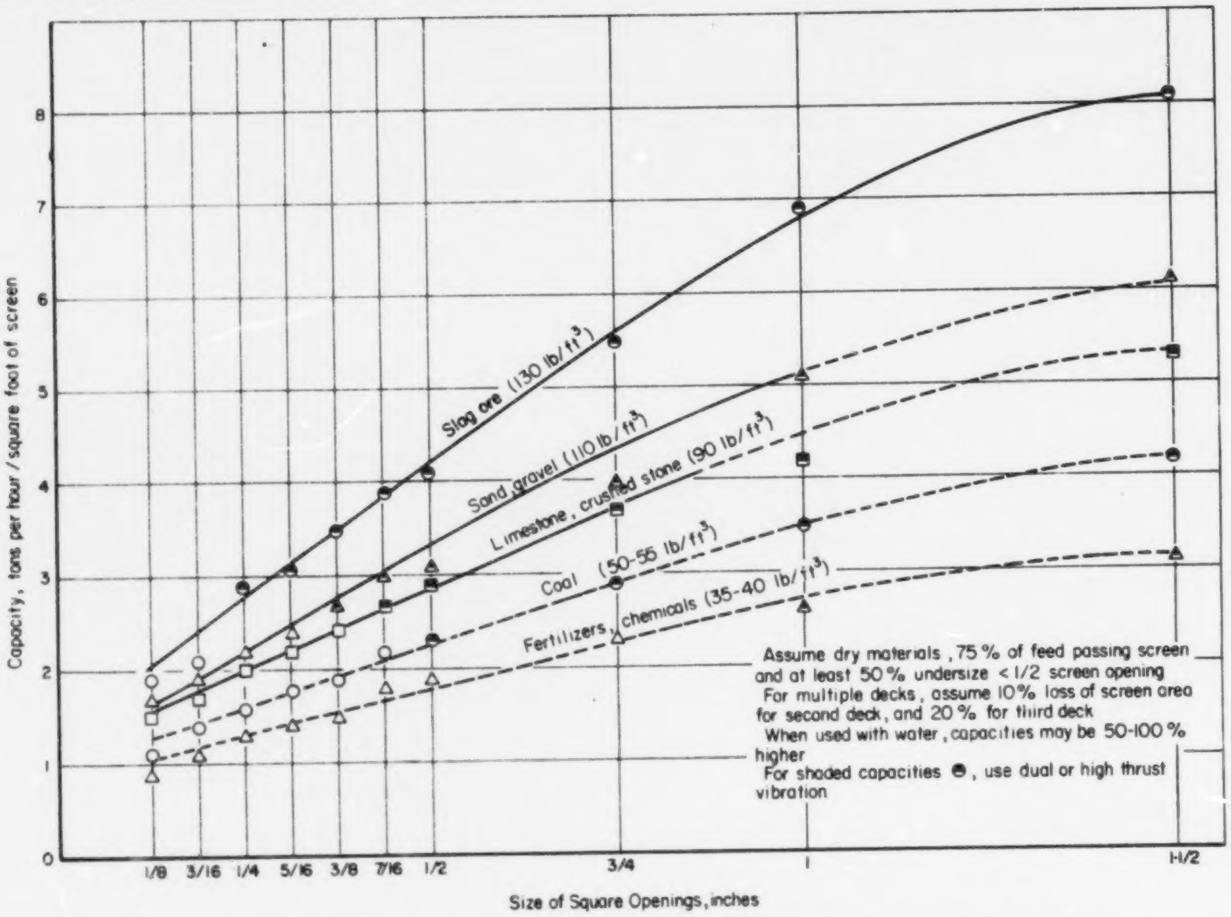
*Syntron Company and Denver Equipment Company.



Assume dry materials, 75 % of feed passing screen and at least 50 % undersize < 1/2 screen opening

For multiple decks, assume 10% loss of screen area for second deck, and 20 % for third deck

When used with water, capacities may be 50-100 % higher

For shaded capacities ●, use dual or high thrust vibration

FIGURE 27. *Capacity of Syntron vibrating screens. (Data supplied by Syntron Company.)*

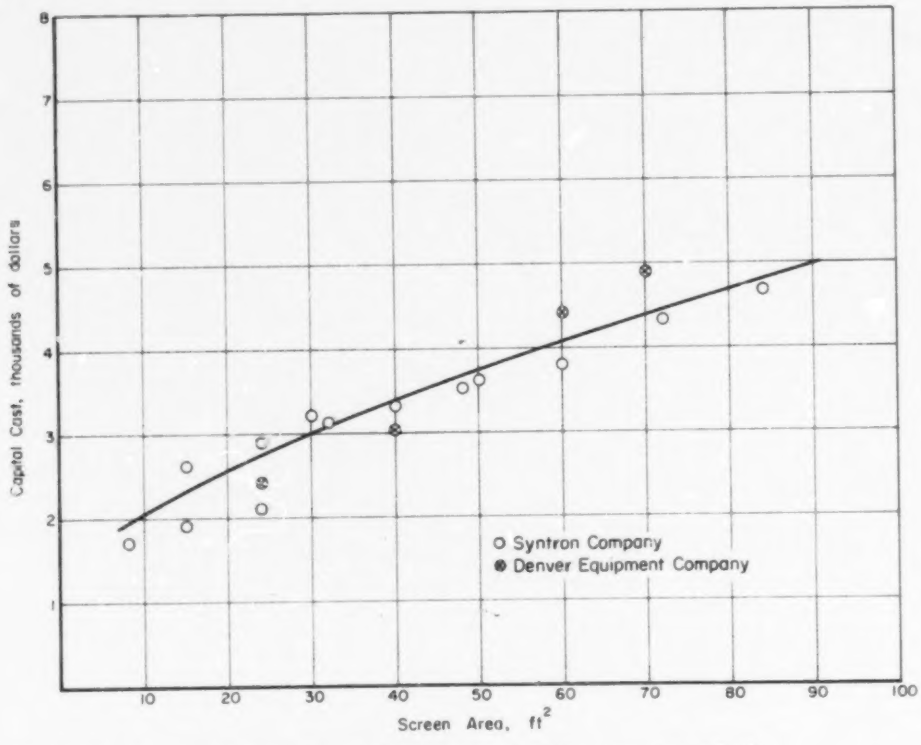


FIGURE 28. *Capital costs of single-deck vibrating screens. (Data supplied by Syntron Company and Denver Equipment Company.)*

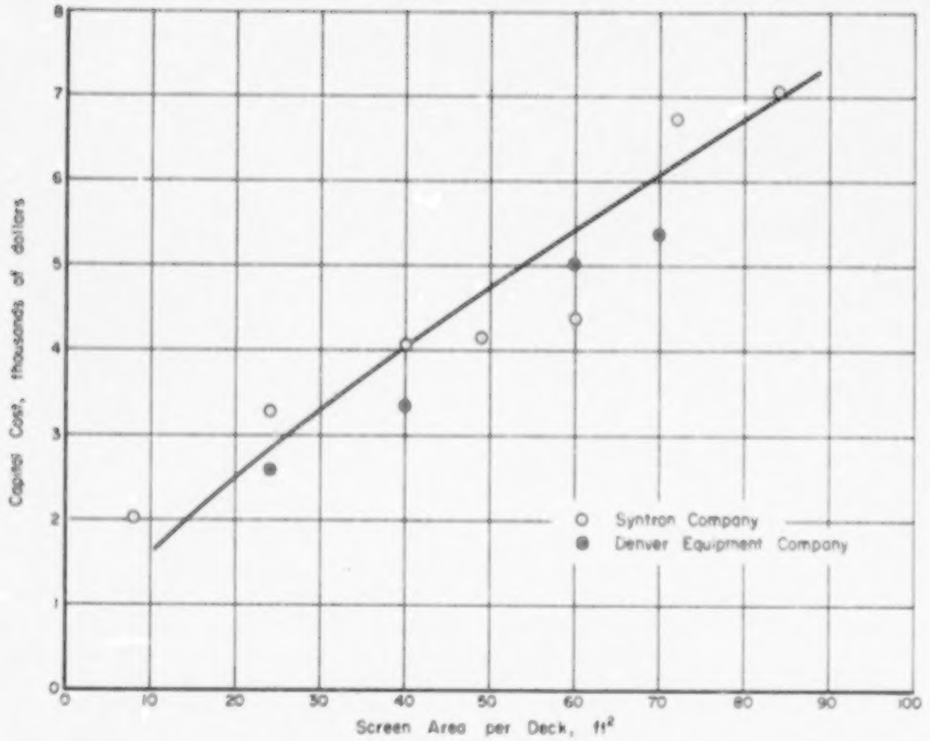


FIGURE 29. *Capital costs of double-deck vibrating screens. (Data supplied by Syntron Company and Denver Equipment Company.)*

water is removed by permitting flow over a weir. The overflow contains the fines to be separated. The larger materials, termed sands, settle and are collected and removed by means of the revolving spiral. As indicated, the sand-making mechanism may be either a double or single spiral. In the single-spiral assembly, the sands are conveyed up one side of a tank, leaving a drainage channel between the spiral and the tank on the opposite side. In the double-spiral machines, the spirals rotate in such a manner that the sands are conveyed up the center of the tank between the spirals. Feed enters through an opening on one or both sides of the tank. Overflow is discharged at the lower end over an adjustable weir. Potential applications in solid waste processing to effect separations based on differences in specific gravity should be evident from the equipment descriptions outlined above, although no known applications have been encountered.

A typical spiral classifier is shown (Figure 30). The selection of equipment and the design of classification systems hinge on several variables. These include: (1) tonnage of fine and coarse materials to be processed; (2) mesh size at which separation is to be made; (3) settling rates of materials to be processed; (4) solids concentration and particle-size distribution in the slurry; (5) moisture/solids content of sands and overflows; (6) specific gravity of materials being processed; (7) spiral revolution rate; (8) weir width and depth (and hence pool size); (9) tank slope; (10) pool

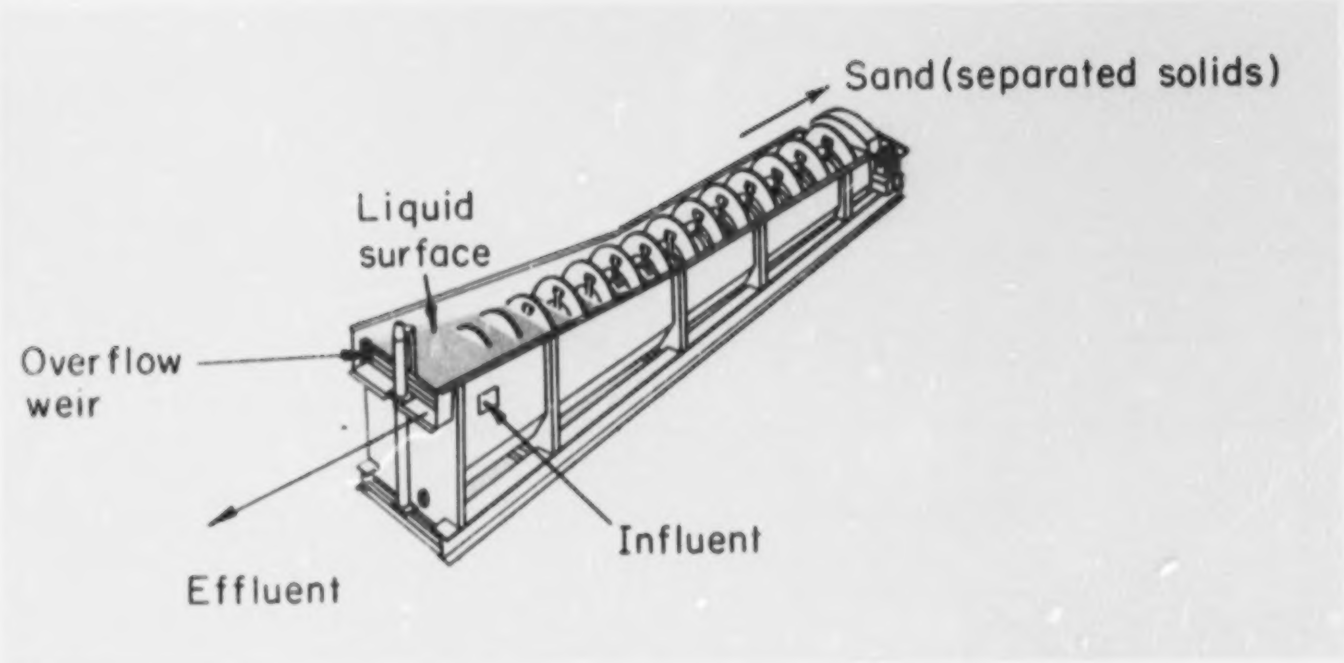


FIGURE 30. *Denver spiral classifier. (Source: Denver Equipment Company.)*

TABLE 13

CAPACITY OF SPIRAL CLASSIFIERS*

Spiral diameter (in.)	Tons of sands per hr (approximately)
24	1–3
36	3–10
48	9–26
54	10–31
72	28–85

*Source: Denver Equipment Company.

area (i.e., percent of spiral surface submerged); (11) spiral length. Spiral sizes are related in terms of spiral diameter. Capacities are normally given in terms of tons of sand per hr. Capacities of equipment vary for typical minerals beneficiation applications (Table 13).

Capital costs of spiral classifiers are a function of spiral size (Figure 31). Operating costs are mainly related to power consumption; power requirements for these spiral classifiers range from 2 to 15 horsepower.

GRAVITY SEPARATION

Flotation. Flotation is basically a gravity separation process; although, as seen from the brief discussion of the process mechanisms outlined below, other than pure gravity-related phenomena are employed. Flotation effects the separation of dissimilar solids through the selective affinity of their surfaces, properly modified by reagents, if necessary, for air and water. Detailed process mechanisms are discussed elsewhere and will not be repeated here.[17] The first step in flotation is size reduction to physically free from one another the materials to be separated. An aqueous slurry or pulp is then created and air bubbles are introduced into the bottom of a tank containing the mixture. By the selection of flotation agents, the material which one desires to remove is made selectively hydrophobic imparting to it a greater affinity for air than water. As the bubbles rise in the slurry, the fraction to be separated is carried to the surface along with the bubbles and is then collected in a suitable fashion.

Flotation equipment and processing systems were developed initially for minerals beneficiation, and this is still the major application of flotation technology. Nevertheless, the operation is being extended into other fields such as the separation of wheat hulls from kernels and the deinking of newspaper.

Existing flotation technology is concerned almost entirely with the separation of finely divided material, usually varying in size from 20 to under 200 mesh. Mineral solids require fine grinding to physically free mineral crystals from other portions of the ore. Surface conditions are important, and it is necessary that the air bubbles support the solid in the slurry. As indicated, flotation agents are employed to impart hydrophobic properties to materials to be separated. At least 60 flotation agents are

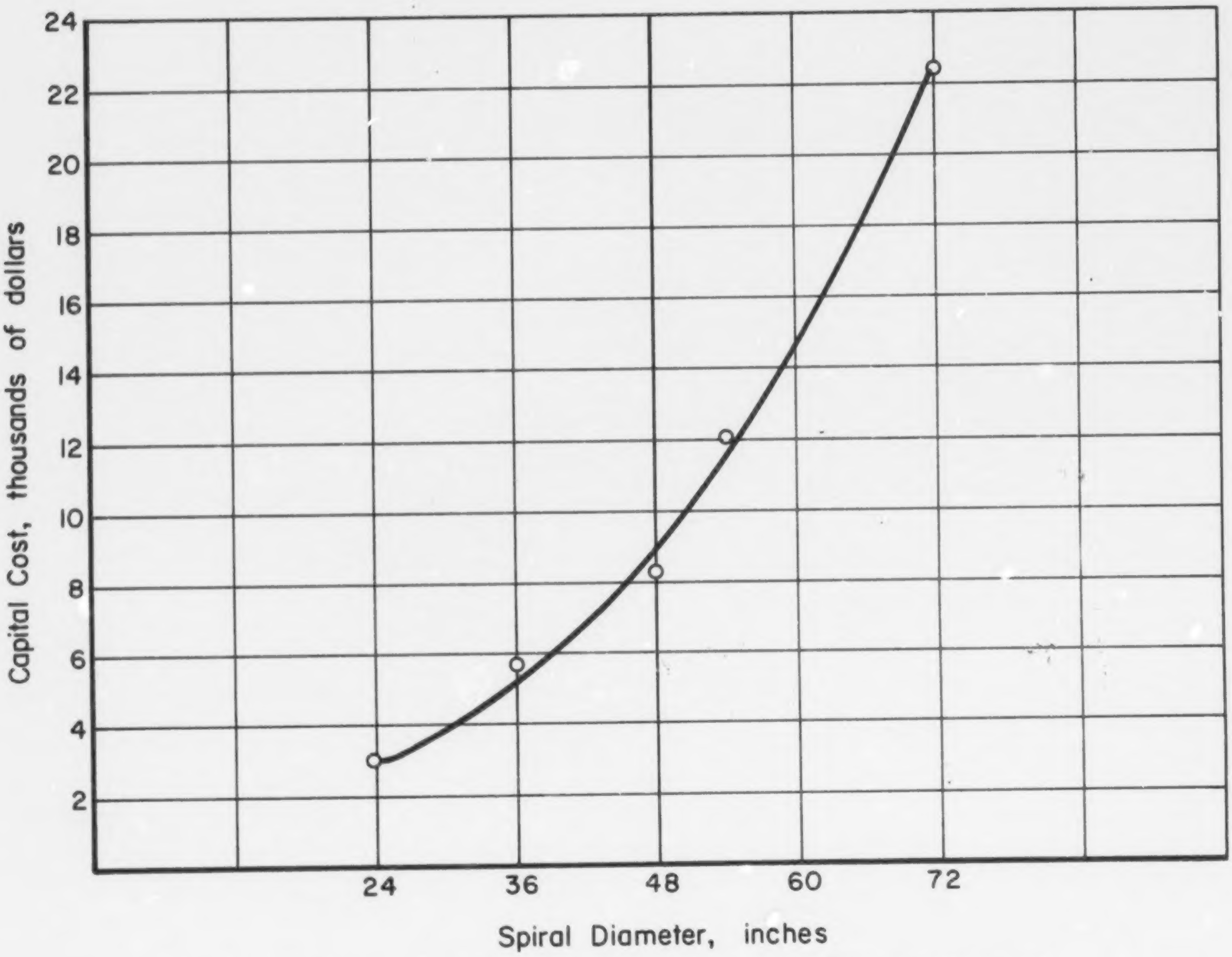


FIGURE 31. *Capital cost of Denver spiral classifiers. (Data supplied by Denver Equipment Company.)*

TABLE 14

FLOTATION AGENTS COMMONLY USED IN MINERALS BENEFICIATION*

1. Acintol FA-1 tall oil fatty acid
2. Acintol FA-2 tall oil fatty acid
3. Aero Depressant 610
4. Aero Depressant 633
5. Aerofloc 550
6. Aerofloat 15
7. Aerofloat 25
8. Aerofloat 31
9. Aerofloat 208
10. Aerofloat 238
11. Aero Promoter 404
12. Aero Promoter 710
13. Aero Promoter 801
14. Aero Promoter 825
15. Aerosol GFC
16. Amine D acetate
17. Armac C
18. Armac T
19. Armac TD
20. Armacflote P
21. Barrett No. 4 Creosote
22. Barrett No. 634 Creosote
23. Benefite 89
24. Caustic soda (NaOH)
25. Copper
26. Cresylic acid
27. Duomac T
28. Dowfroth 250
29. Formonyte 602
30. Formonyte 616
31. Lime
32. Merasperse CB
33. Methyl isobutyl carbinol
34. Minerec B
35. Orzan S
36. Pamak 1
37. Pamak 4
38. Pearl starch
39. Pine oil, Yarmor F
40. Quebracho
41. Sepa an MGL
42. Soda ash
43. Sodium Aerofloat
44. Sodium dichromate
45. Sodium silicate
46. Sodium sulfide
47. Sodium sulfite
48. Stadex Dextrin 120
49. Superfloc 16
50. Superfloc 20
51. Thiocarbanilide 130
52. Z-3, potassium ethyl xanthate
53. Z-4, sodium ethyl xanthate
54. Z-5, potassium sec-amyl xanthate
55. Z-6, potassium amyl xanthate
56. Z-11, sodium isopropyl xanthate
57. Z-12, sodium sec-butyl xanthate
58. Z-14, sodium isobutyl xanthate
59. Z-200
60. Zinc sulfate

*Source: Denver Equipment Company.

known to be used in minerals beneficiation (Table 14).

The selection of flotation equipment and the design of flotation systems are highly empirical in that most design variables need to be selected upon the basis of experimental data. Factors which need to be determined before flotation capacity for a given application can be determined are specific gravity of the solids being treated, optimum percent solids in the aqueous slurry, particle size, retention time, aeration rates, and flotation agents. The degree of separation obtained in a given application is a function of complex interrelationships between each of these factors and the surface properties of the material being separated. Consequently, process design usually involves extensive laboratory-scale experimental work to find the optimum combination of the several variables involved. This is true even for applications within the minerals beneficiation field for which a fair amount of operational experience is documented. For the reasons indicated above, and because no laboratory or operational experience exists, very little can be said about expected performance and costs for separating various components in solid waste by flotation. Possible applications which come to mind include the cleaning of compost; separation of glass and/or nonferrous metals from mixed refuse or from by-products such as compost; and the separation of paper from mixed refuse, as well as various undefined separations which may be required in the manufacture of selected by-products.

The only indication of experimental studies related to the application of flotation to municipal solid waste recovery is work being done by the U.S. Bureau of Mines in College Park, Maryland, which is discussed in a later section. These studies are concerned with the recovery of metals and other materials from municipal incinerator residues. Although this is a very specialized form of solid waste, the experimental data generated by these studies should provide valuable guidelines as to the merits of this as well as other potential applications of flotation technology to solid waste recovery.

A related application is reportedly being studied by Luria Brothers, automobile salvagers, for the removal and separation of nonferrous metals and also for the cleaning of ferrous and nonferrous products.[18] Details of this work are proprietary, and it was not possible to obtain additional information during the course of this study.

Capital costs of flotation are mainly for tankage and aeration equipment; operating costs are mainly for power to provide aeration. Before one can determine tankage, and hence capital costs, many of the design variables mentioned above must be determined. Once one knows the throughput rates, retention times, and percent solids, it is rather straightforward to calculate capacities on the basis of a mass balance as follows:

Letting:
C = required flotation capacity (cu ft)
Q = material throughput rate (tons of solids/8-hr day)
γ = specific gravity of solids
s = percent solids ÷ 100
t = retention time (min)
one may derive the relationship:

$$C = 0.0688 \left[\frac{1}{\gamma} + \frac{1-s}{s} \right] Qt.$$

Based upon experience with minerals beneficiation, one manufacturer estimated that retention times in processing solid waste could vary from 5 to 20 min. and optimum solids content from 5 to 20 percent. All of these variables affect required flotation capacity (Figure 32). It is seen that

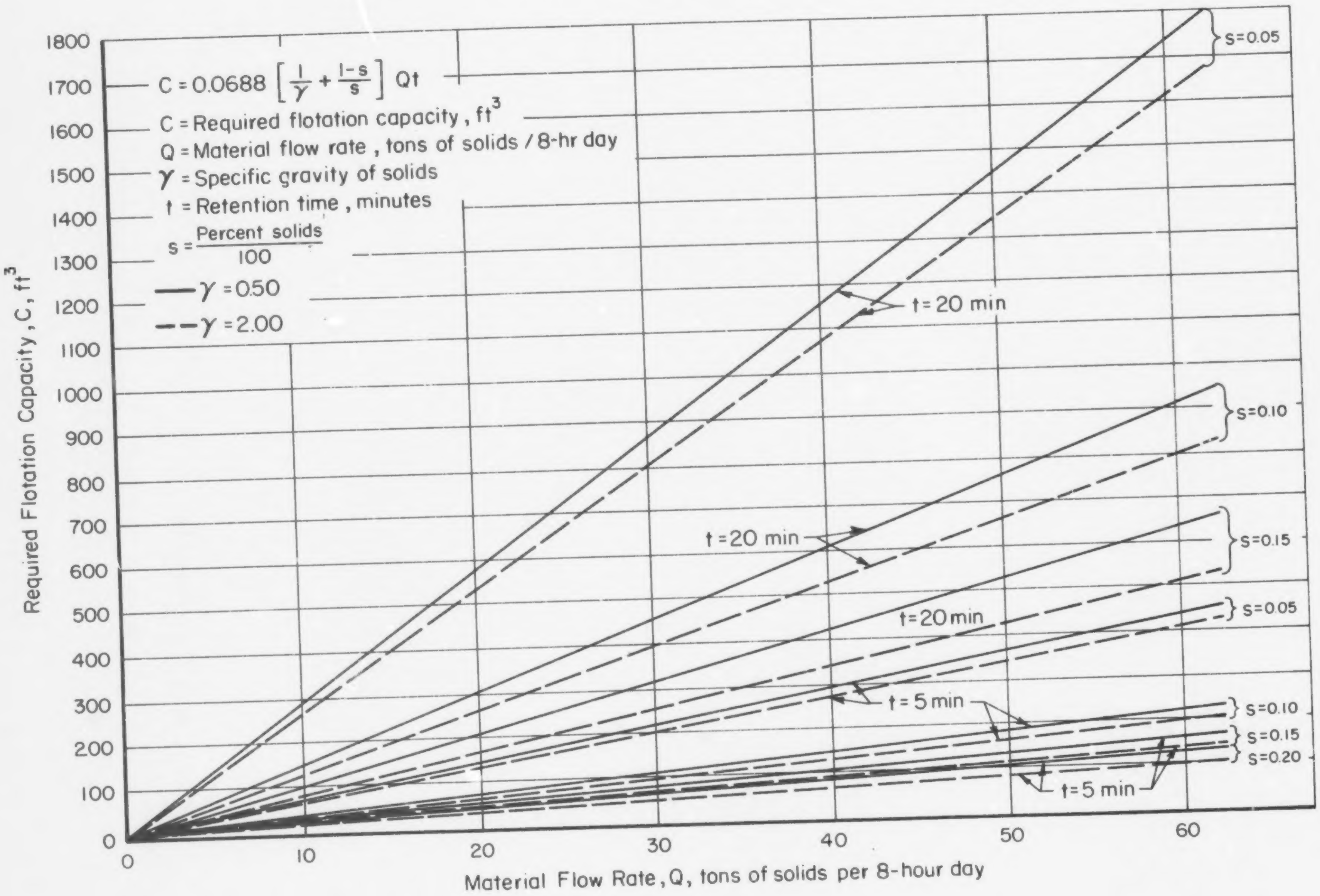


FIGURE 32. *Flotation capacity requirements.*

an extremely wide range in required capacity is indicated, further demonstrating the need for experimental data before even order-of-magnitude cost estimates can be generated. The capital cost of Denver flotation equipment may be related to capacity (Figure 33).

As previously indicated, operating costs consist almost entirely of power costs. Power requirements to operate pumps, mixers, and compressors are functions of flotation capacity (Figure 34).

Dense media. Dense media separation, sometimes referred to as the sink-float process, is a gravity separation technique for separating materials having a specific gravity higher than that of the medium employed from those having a specific gravity lower than that of the medium employed. Particle sizes in the feed for minerals beneficiation applications range from 3 in. down to 10 mesh (0.066 in.). It is generally true that differences in the specific gravity of the materials to be separated can be less than that required for efficient separations by jigging or tabling. Dense media have been used extensively in laboratory separations and for industrial applications such as ore beneficiation.

There are two types of heavy media used for separation: (1) solids-water systems, and (2) organic liquids. Suspensions of solids in water usually consist of ferrosilicon, magnetite, or galena. When ground to suitable fineness and mixed with water in correct proportion, these high specific gravity solids provide a medium that closely duplicates the fluid characteristics of a true heavy liquid. Recent trends have favored the use of magnetite and ferrosilicon since these materials can be more easily reclaimed and are lower in initial cost. Specific gravities of dense media attainable with suspensions of these materials range from 1.25 to 3.4. Magnetite alone is used to obtain specific gravities in the 1.25 to 2.20 range; magnetite and ferrosilicon mixtures are used to obtain specific gravities in the 2.20 to 2.85 range; and ferrosilicon alone is used for specific gravities >2.85. Process details are available in the literature.[19]

Applications of dense media separation are not sufficiently widespread that typical industrial performance and cost data are available. Applications to solid waste processing are nonexistent, but various potential applications exist. The work being conducted by the Bureau of Mines at College Park, Maryland, includes plans for some experimental studies to be conducted at an unspecified time in the future to investigate the recovery of incinerator residues by heavy media techniques. Similarly, research mentioned earlier may also develop information in this technical area, as related to the cleaning of automobile scrap and the recovery of nonferrous metals.[19]

In order for dense media separation to be economical, the suspension solids must be recovered. Magnetite and ferrosilicon are recovered by magnetic means, and galena is recovered by froth flotation.

Ferrosilicon is the most widely used material. In order to maintain magnetic properties essential to recovery and to prevent rusting, a 15 percent silicon content having a specific gravity of approximately 6.8 has been found most suitable. Where the separation is between 2.6 and 2.9, the ferrosilicon is ground to <100 mesh (0.0059 in.), and for separation at higher specific gravities ~3.2), <65 mesh (0.0083 in.) is employed.

Organic liquids (primarily chlorinated and brominated hydrocarbons) are true heavy media; but their industrial use has many drawbacks, including health hazards from inhalation of fumes, danger of contact with an operator's skin, losses by splash and evaporation, corrosive action, chemical breakdown, and the high cost of materials. Typical heavy media liquids and their properties have been tabulated (Table 15). Again, in the interest of economy, it is necessary to recover as much of the material as possible. Typical losses for minerals beneficiation on pilot and in small mill operations run about 1 lb per ton of material processed.

Stoners. Stoners are devices for separating material primarily on the basis of differences in specific gravity. Only one manufacturer is in the United States at present.* As indicated below, particle size and shape also contribute to the basic separation phenomena employed. Stoners have been applied only recently (late 1967) to solid waste processing with reasonable success. Applications to date have been limited to the removal of glass and nonmetallics from compost. As of this writing, two compost plants, one in Altoona, Pennsylvania, and one in Houston, Texas, are employing stoners in their processing systems.

Stoners were originally developed,

TABLE 15

PROPERTIES OF HEAVY ORGANIC LIQUIDS USED IN HEAVY MEDIA SEPARATION

Compound	Specific gravity	Approximate cost* (dollars per lb)
Tetra-bromo-ethane (acetylene tetrabromide)	2.96	0.53
Bromoform	2.89	----------
Methyl bromide	2.48	0.57–0.64
Ethylene dibromide	2.17	0.285
Pentachloroethane (pentalin)	1.67	----------
Tetrachloro-methane (carbontetrachloride)	1.50	0.1075
Trichloroethylene	1.46	0.0925

*From Oil, Paint, and Drug Reporter, May 6 and 13, 1967.

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*Sutton, Steele, and Steele, Dallas, Texas.

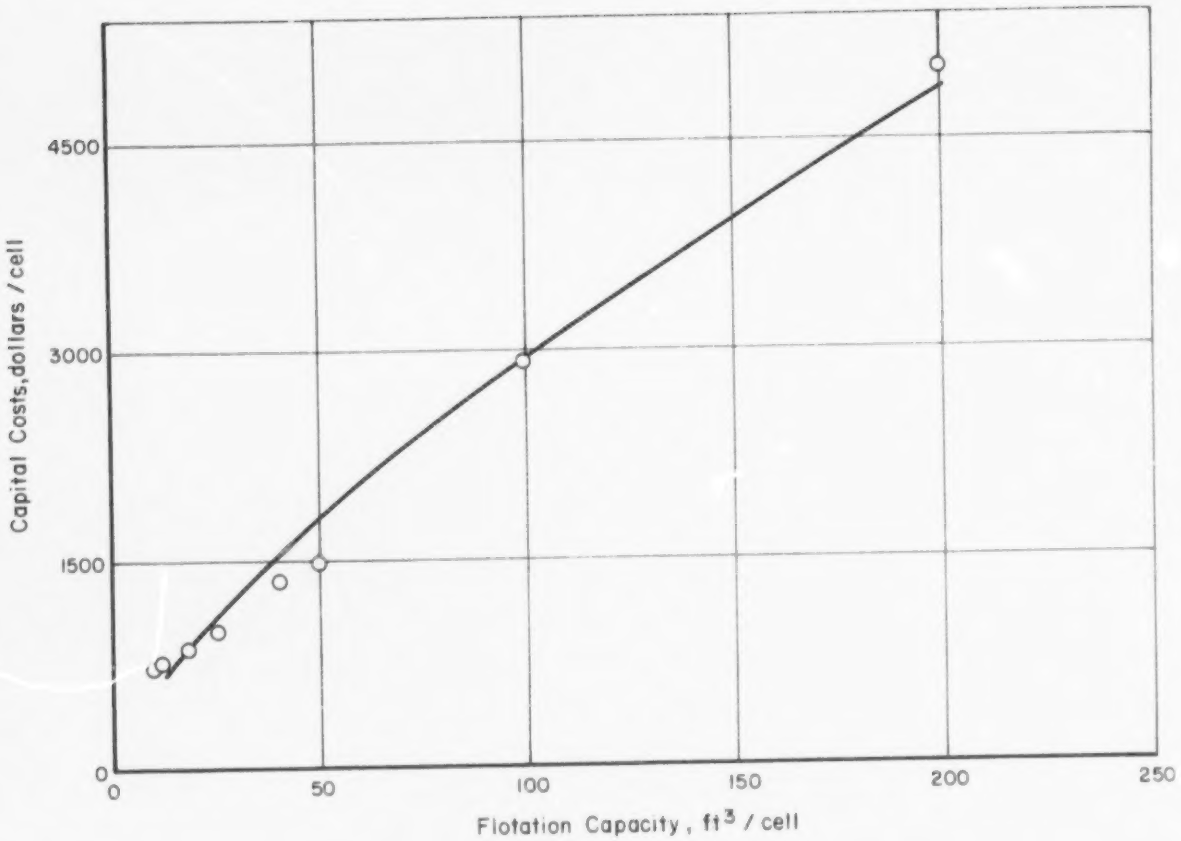


FIGURE 33. *Flotation capacity capital costs. (Data supplied by Denver Equipment Company.)*

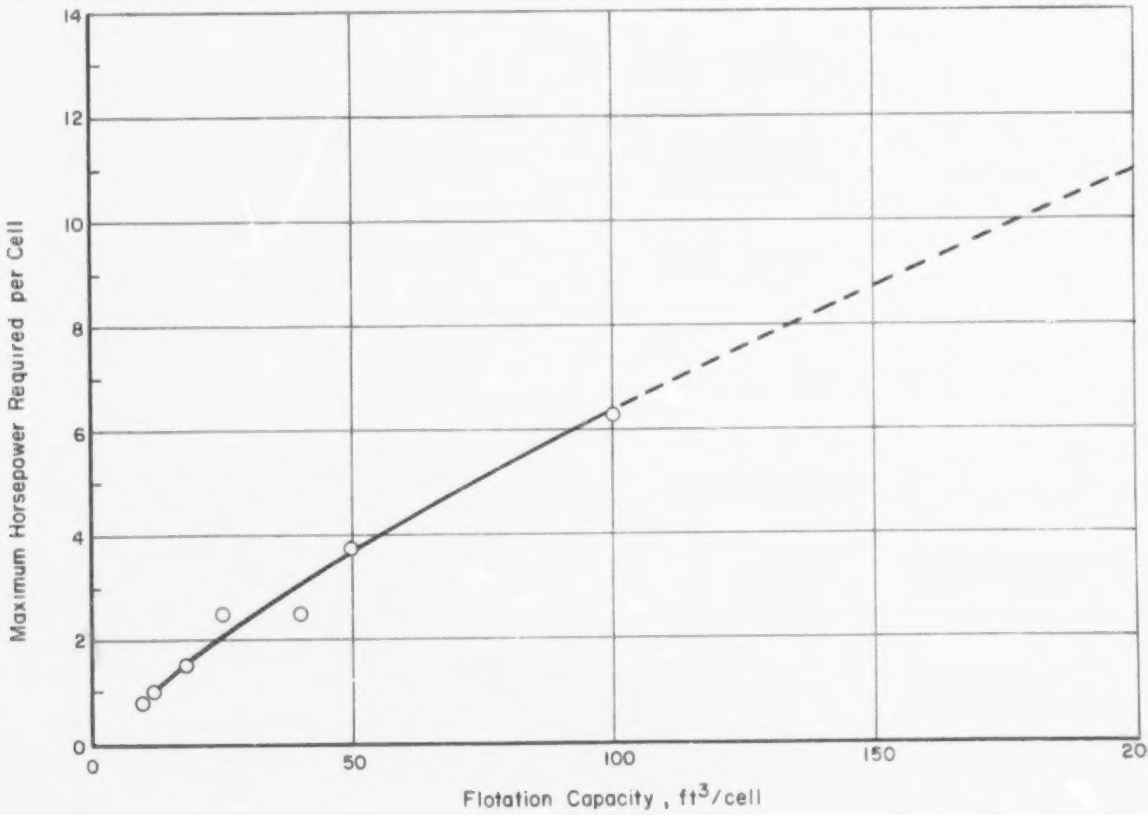


FIGURE 34. *Flotation power requirements. (Data supplied by Denver Equipment Company.)*

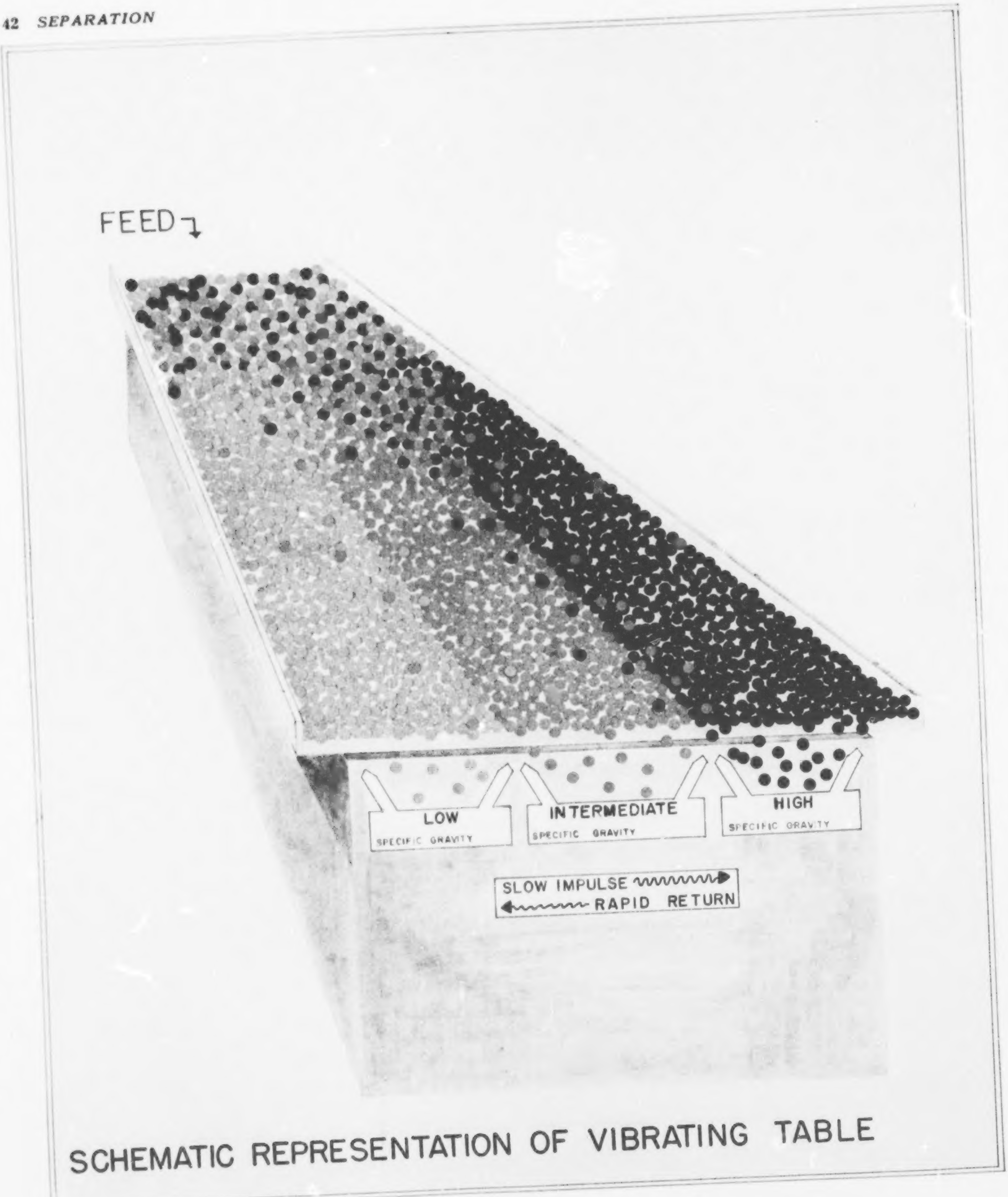

FEED
LOW
SPECIFIC GRAVITY
INTERMEDIATE
SPECIFIC GRAVITY
HIGH
SPECIFIC GRAVITY
SLOW IMPULSE
RAPID RETURN
SCHEMATIC REPRESENTATION OF VIBRATING TABLE

FIGURE 35. *Schematic representation of dry vibrating table.*

TABLE 16

SUMMARY OF PATENTS RELATED TO STONERS

Patent No.	Title
797, 239	Dry concentrating table.
898, 020	Separating table.
979, 046	Process of concentrating comminuted material.
1, 073, 644	Separating table and process of separation.
1, 133, 760	Process of and apparatus for separating and grading seeds.
1, 315, 881	Process of and apparatus for separating and grading material.
1, 574, 637	Air baffle.
1, 632, 520	Process of and apparatus for separating, cleaning, and grading all kinds of nuts, cereals, and legumes.
2, 137, 678	Apparatus for separating a mass of seeds of varied characteristics.
2, 137, 679	Process for separating a mass of seeds of varied characteristics.

and are traditionally employed, for the removal of stones, shells, and other heavy materials from nuts, seeds, grains, and other similar light products. A stoner is basically a dry vibrating table that operates by passing a stream of air upward through an inclined screen or perforated table (Figure 35). Feed enters near the top of the inclined screen. Lighter particles are buoyed up by the air passing through the screen and flow downward to the lower end where they are discharged. The inclined screen vibrates in an oscillating motion which causes the dense particles to migrate upward along the screen surface and discharge over the higher end of the table. By proper installation of baffles and the selection of the point where feed material enters, a feed stream containing materials with different specific gravities can be separated into several product streams. In order to effect good separation, particle size must be controlled rather closely. Otherwise, large less dense particles may end up in the heavy fraction and small heavy particles may end up in the light fraction. Size control is normally accomplished by screening. Depending on the material, particle sizes in the range $\frac{1}{16}$ to 2 in. can be accommodated.

Basic patents upon which stoner designs are based have been summarized (Table 16). As indicated, existing applications of stoners to the solid waste processing field are limited to the separation of glass from compost. At the Altoona FAM Plant in Altoona, Pennsylvania, a small laboratory scale unit is employed to process 2 to 3 tons/hr. Prior to processing in the stoner, the compost is pelletized and screened through a vibrating screen having $\frac{3}{16}$-in.-diameter openings. Material passing through the screen is fed to the stoner. The heavy fraction from the stoner, amounting to about 5 percent of the feed, has a bulk density of about 1.2 lb/cu ft, whereas the light compost product has a bulk density of 0.6 lb/cu ft.

A second similar application is at the Lone Star Organics, Inc., compost plant in Houston, Texas. Although the system is still under development, a flow sheet indicating approximate operating conditions is provided (Figure 36). The compost feed to the system is not pelletized, but is taken directly from the digesters and subjected to a final size reduction. Because the application is so new, operating conditions are continually being modified and the process flow sheet cannot be interpreted as firm. For example, inputs to the system as high as 25 tons per hr have been tried, and screen size openings on the lower screen have been varied from $\frac{5}{16}$ to $\frac{3}{4}$ in. In addition, the extent of regrinding and recycling depends on the market for the coarse compost. One market which has consumed a major portion of the coarse product is highway landscaping.

The stoner used at the Houston plant is the Mark IV model manufactured by Sutton, Steele, and Steele (Figure 37).

Capital costs for the major equipment items at the Houston plant are as follows:

Screening equipment	$8, 000
Two Mark IV stoners at $10,000 each	20, 000
	$28, 000

Assuming 10-yr life and 6 percent interest, amortized capital costs amount to $0.10–0.15 per ton of compost (feed) processed. Power requirements are very low—on the order of 1 hp (0.75 kw) per ton per hr—and so operating costs are also very low.

Capital costs of various size stoners manufactured by Sutton, Steele, and Steele do not exhibit normal economies of scale (Figure 38); this is presumably due to the more flexible capabilities of the larger production-scale units and limitations on the smaller ones which are intended for laboratory use.

Wilfley tables. Wilfley tables are similar to stoners in many ways and effect separations of solids mainly upon differences in specific gravity and to a lesser extent upon shape and size of the particles being processed (Figure 39). The main difference between Wilfley tables and stoners is that water instead of air is used as the buoying medium. Wilfley tables are used mostly in minerals beneficiation to concentrate metallic ores in the size range from 6 mesh (0.132 in.) to 150 mesh (0.0041 in.) but can be used to separate lighter materials such as coal (and presumably solid waste) of considerably larger size.

Separation is effected by flowing a pulp across a riffled plane surface, which is inclined slightly (2 to 5 degrees) from the horizontal in the direction perpendicular to the riffles. The table is vibrated in the direction of the long axis (along the riffles) and washed by water flowing at right angles to the direction of vibration. Lighter materials buoyed by the water wash over the riffles and travel to the low side of the table. The heavier particles are collected in the riffles. The vibrating motion employs a slow stroke and rapid return, thereby causing the heavy particles in the riffles to migrate toward the end of the table (Figure 39).

During operation several "bands" of materials of varying specific gravities will develop on the surface of the table, and each may be collected separately by the proper placing of baffles. It is seldom possible to achieve a sharp separation, and materials at the boundaries of the various bands are mixtures termed "middlings." To achieve high degrees of separation, these middlings must be recycled to the feed. Tables are usually surfaced with hard linoleum or rubber. Riffles may be wooden or rubber strips.

Although the potential exists, Wilfley tables have not been applied to the processing of solid waste. One exception to this statement is work recently initiated by the Bureau of Mines on municipal incinerator residue recovery. However, at the time of the writing no data were available concerning this work.

The cost of tabling ores is very low. Tables with relatively large capacities are not expensive and power requirements are minimal. A comparison of selected information on the two tables manufactured by Denver Equipment

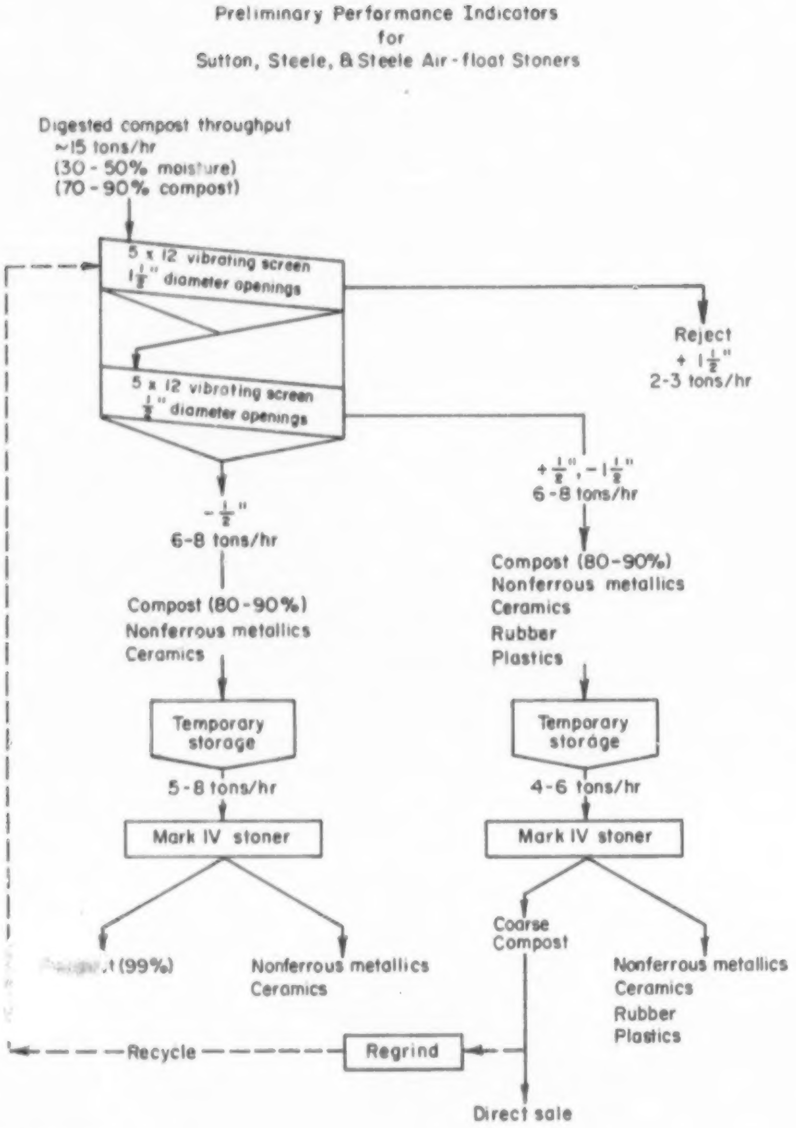

Preliminary Performance Indicators
for
Sutton, Steele, & Steele Air-float Stoners
Digested compost throughput
~15 tons/hr
(30 - 50% moisture)
(70 - 90% compost)
5 x 12 vibrating screen
1½" diameter openings
Reject
+ 1½"
2-3 tons/hr
5 x 12 vibrating screen
½" diameter openings
-½"
6-8 tons/hr
+½", -1½"
6-8 tons/hr
Compost (80-90%)
Nonferrous metallics
Ceramics
Compost (80-90%)
Nonferrous metallics
Ceramics
Rubber
Plastics
Temporary storage
Temporary storage
5-8 tons/hr
4-6 tons/hr
Mark IV stoner
Mark IV stoner
Compost (99%)
Nonferrous metallics
Ceramics
Coarse Compost
Nonferrous metallics
Ceramics
Rubber
Plastics
Recycle
Regrind
Direct sale

FIGURE 36. *Approximate process flows sheet for Lone Star Organics, Inc., compost plant, Houston, Texas.*

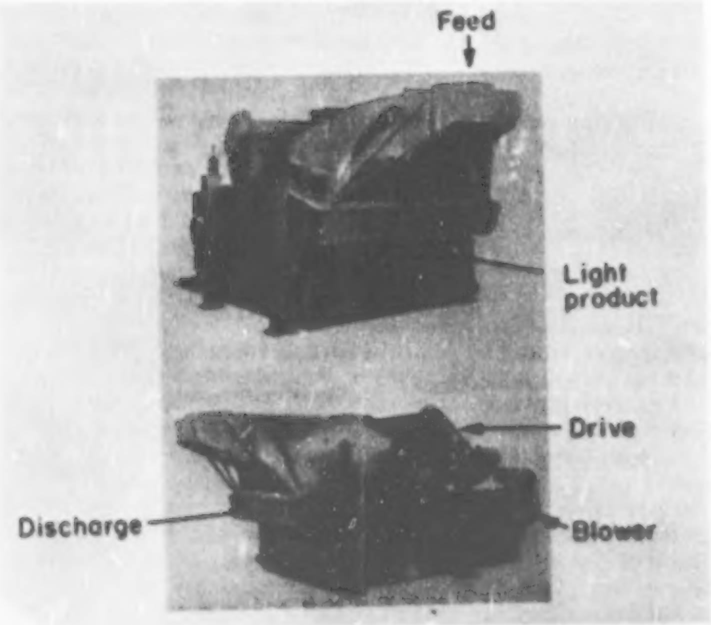

Feed
Light product
Drive
Discharge
Blower

FIGURE 37. *Sutton, Steele, and Steele Mark IV stoner.*

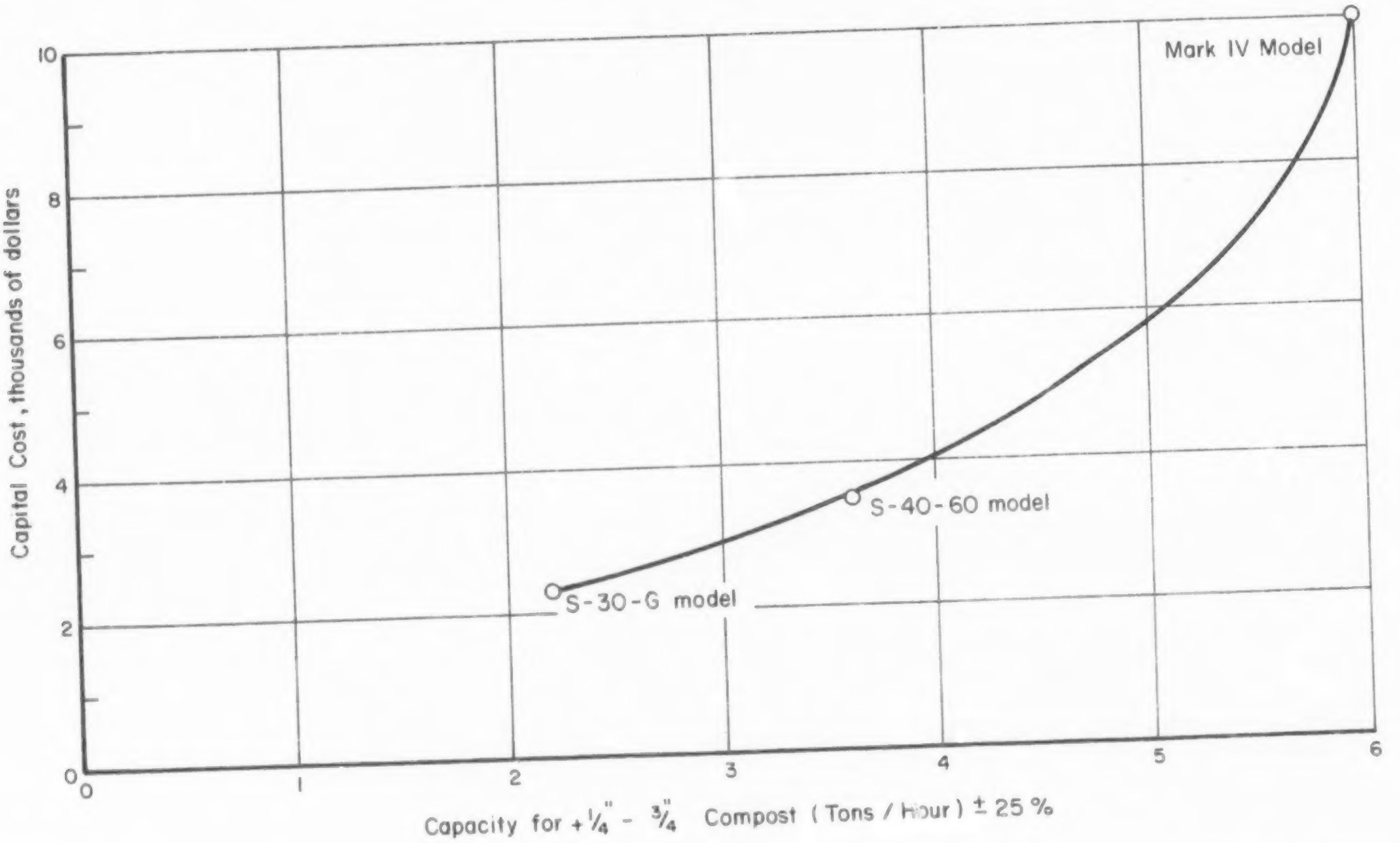


FIGURE 38. *Capital cost of Sutton, Steele, and Steele stoners.*

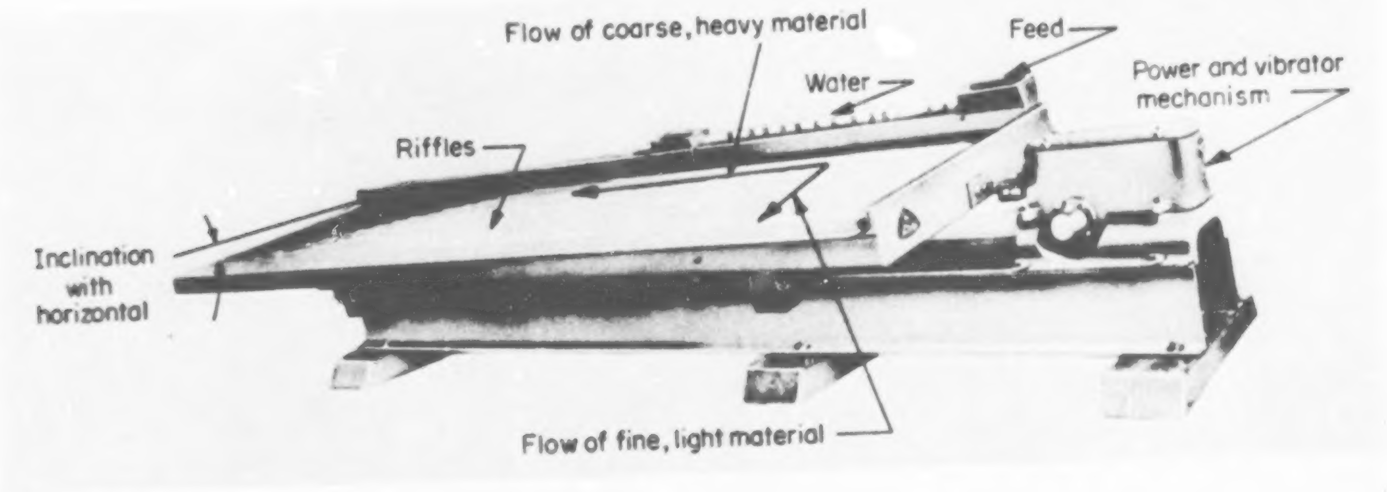

Flow of coarse, heavy material
Feed
Water
Power and vibrator mechanism
Riffles
Inclination with horizontal
Flow of fine, light material

FIGURE 39. *Wilfley table. (Source: Denver Equipment Company.)*

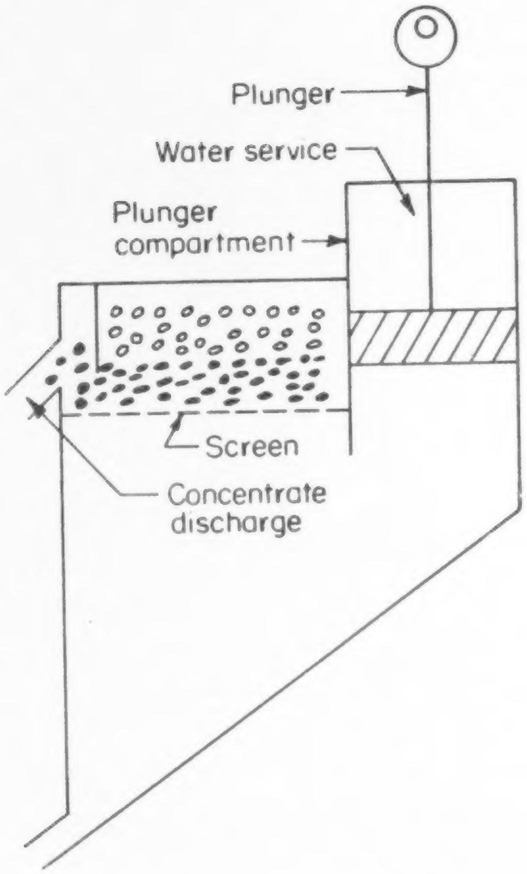
Company indicates significant economies of scale (Table 17).

Mineral jigs. A jig is a mechanical device for separating presized materials of different specific gravities by the pulsation of a stream of liquid through a bed of the material. The liquid on the screen pulsates or jigs up and down, causing repeated expansion and contraction of the bed, thereby causing the heavy material to work to the bottom of the bed and the lighter material to the top. Jigging thus results in the stratification of particles into layers of different densities. Jigging is widely used in minerals beneficiation, but has not been applied to solid waste processing. It is mentioned primarily in the interest of completeness, since the method may be applicable to the recovery of special types of solid waste such as incinerator residues.

A jig consists primarily of a rectangular tank fitted with a horizontal screen slightly below an overflow. The screen may be given a pulsating or jigging motion which causes an alternate upward and downward motion through the suspension. Alternatively the screen may be fixed and the suspension forced upward through the screen by means of a plunger. In either model, solids are lifted free from the screen and allowed to settle for a short period. The material is stratified vertically on the screen and, after a suitable number of cycles, is removed through properly installed baffles and spigots. Particles passing through the screen are fed to a second jig in series for similar processing. Up to six compartments in series are not uncommon in minerals beneficiation.

The feed is introduced over the screen at one side and subjected to a series of short settling periods as it moves across the screen to the overflow. Screen openings are about twice the diameter of the largest particle intended to pass through the screen. A bedding of large, dense particles builds up on the screen. Less dense particles collect on the top of the bed and are washed into the next compartment, if one is provided. If the feed is a size such that only stratification on the screen and no particle passage through the screen are desired, a bed of steel balls is placed upon the screen.

Several jig designs are available and depart in minor ways from the devices and operation described above. Particle sizes capable of being accommodated for minerals beneficiation applications range from fines to 1½-in. Specifications are given



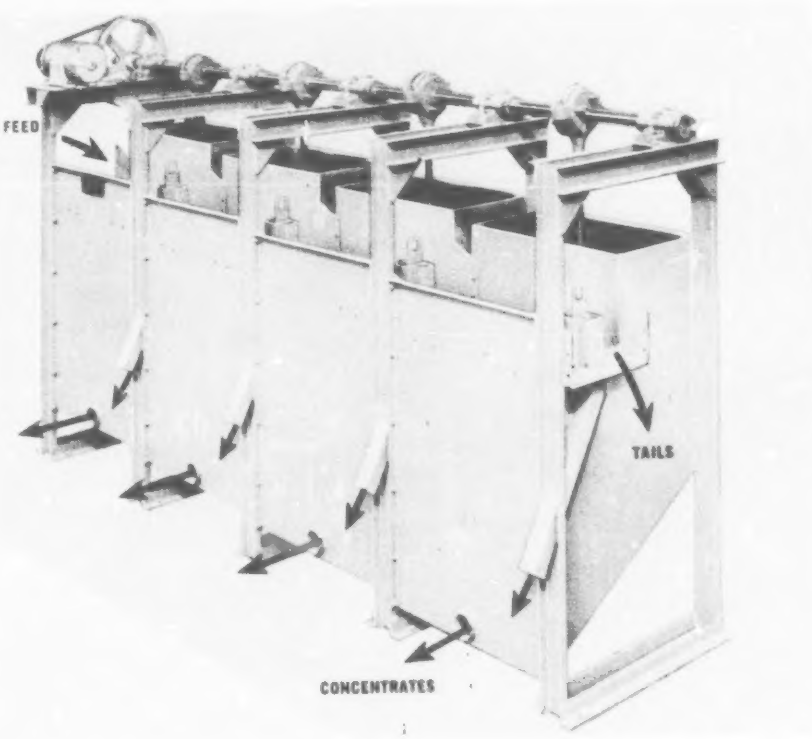


FIGURE 40. *Denver plunger jigs. (Source: Denver Equipment Company.)*

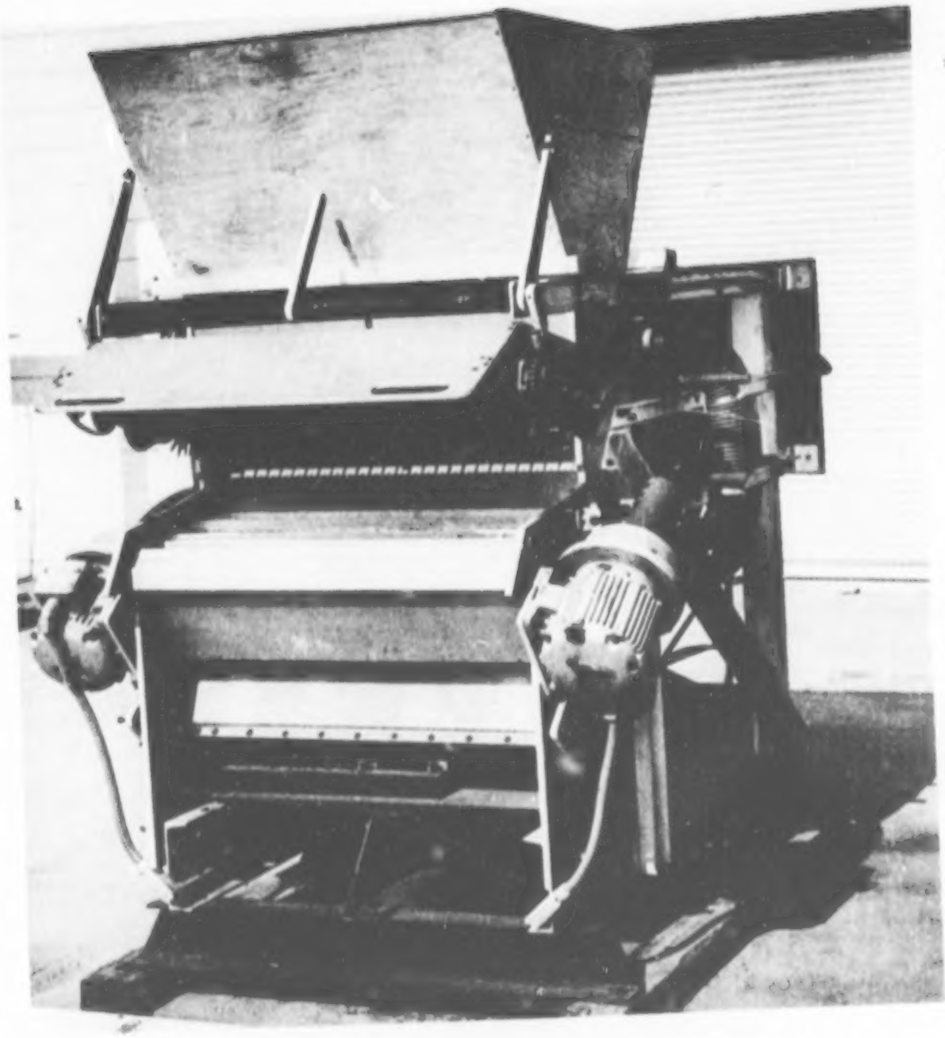


FIGURE 41. *Osborne dry separator.* (*Source: Raymond G. Osborne Laboratories, Inc.*)

TABLE 17

CHARACTERISTICS OF WILFLEY TABLES*

	Model	
	No. 6	No. 12
Capacity (tons/24 hr)	15–150	5–20
Wash water (gpm)	5–20	3–15
Deck size (approx.)	6′ x 15′	3½′ x 7′
Horsepower, motor	1½	1
Capital cost ($)	2,250	1,550

*Source: Denver Equipment Company.

TABLE 18

SPECIFICATIONS FOR DENVER PLUNGER JIGS*

Compartment size (horizontal cross section, in.)	Average capacity (tons/24hr) †,‡	Horsepower	Capital cost (dollars) §
18 x 32	40	1	1, 630
24 x 36	60	1½	2, 150
30 x 36	75	1½	2, 590

* Source: Denver Equipment Company.

† Capacity based on 10 tons of material per 24 hr. Actual capacities for selected minerals are chromite, 4 to 8; pyrite, 6 to 12; galena, 8 to 16; sphalerite, 4 to 8; manganese, 5 to 10; and fluorspar, 1½ to 2.

‡ Water requirements vary from 3 to 10 tons per ton of material treated for ore beneficiation.

§ Multicompartment units can be employed to effect economies of scale.

(Table 18) for Denver plunger jigs (Figure 40).

Osborne dry separator. In principle the Osborne Dry Separator is designed to separate high density materials from low density materials (Figure 41).[30] It was used and was reported successful for removing glass and other similar fractions from compost produced at the General Conversion Systems compost plant during its operation in San Fernando, California, during the period 1963 to 1964 (Figure 41). Successful applications are also claimed for the separation of gold, tungsten, and other minerals.

In concept the device is a jig or pulsed, hindered settling separator. It is very similar to the wet mineral jig, with the exception that air is used as the working medium instead of water.

Cost and performance data are available for the unit used in San Fernando (Table 19).

Fluidized bed separator. Another interesting gravity separation technique developed in England, which has received brief mention in the literature, is a process which employs a fluidized bed of dry materials as a working medium.[31] Materials heavier than the powder medium sink, while lighter materials are carried along. The device was developed specifically for salvaging copper from used cables after grinding. Efforts during the course of this study to obtain additional information were not successful.

OPTICAL SORTING

Optical sorting machines, which separate particles on the basis of color (surface light-reflectional proper-

TABLE 19

CHARACTERISTICS OF THE OSBORNE DRY SEPARATOR*

Size:
  Length—7 ft, 7 in.
  Width—5 ft, 0 in.
  Height—7 ft, 3 in.
Feed rate—based on composed municipal solid waste:
  1½ tons per hr
Particle size:
  Maximum:
    Inorganic fraction—3/16 in.
    Organic fraction—1 in.
  Minimum:
    Inorganic—1/64 in. Battelle estimates
    Organic—3/16 in. Battelle estimates
Separation:
  90 to 95 percent of the glass, sand, metals, and other heavy fractions are removed from the finished composts
Cost:
  $25,000.00 approximately

*Source: Raymond G. Osborne Laboratories, Inc., Los Angeles, California.

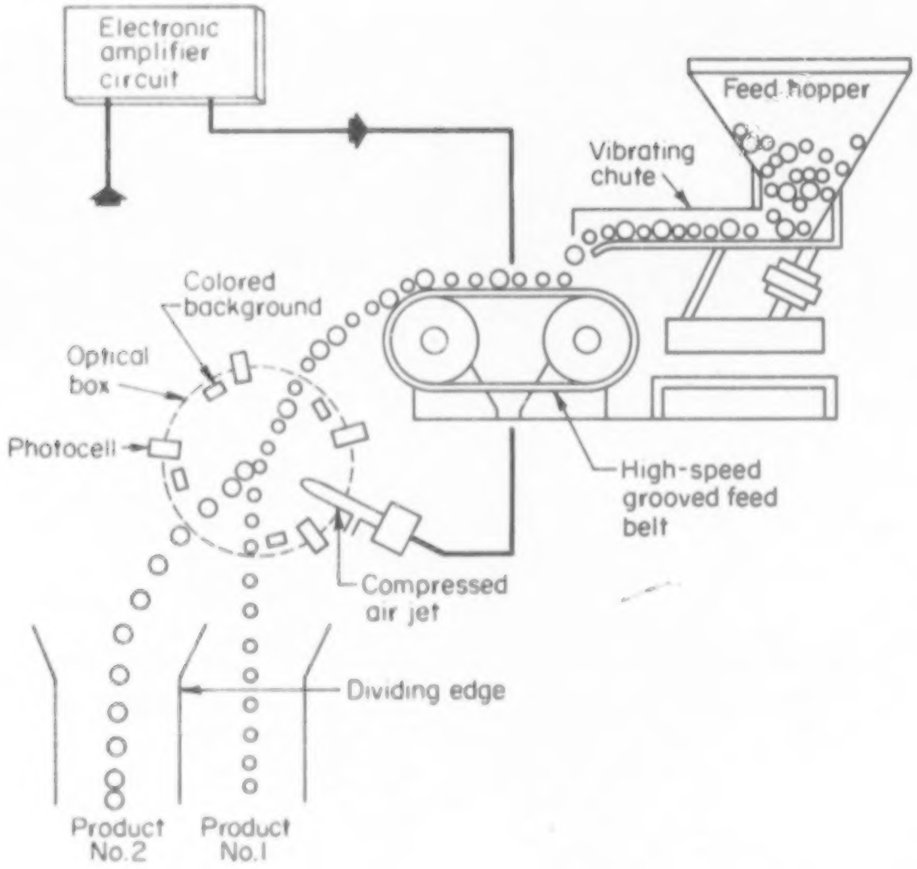


FIGURE 42. *Diagram illustrating the operating principle of the Sortex unit.* (*From* Mining and Minerals Engineering, *1(6):221, Feb. 1965.*)

ties), have been used quite successfully in the agricultural and food processing industries and more recently in minerals beneficiation. Typical applications have included the cleaning and grading of peas, beans, nuts, and seeds and the beneficiation of rock salt and gypsum.

Color sorting machines encountered during this study are manufactured by Sortex Company of North America, Lowell, Michigan. The outlined operating principles (Figure 42) are documented in the literature.[22] The material to be separated is fed into a hopper and delivered by a pair of vibrating chutes to a grooved, endless feed belt moving at high speed. This belt projects the pieces in a continuous stream so that they fall freely through an optical box. Around the sides of this box, four photomultipliers are arranged and suitable illumination is provided. Each photocell head is aimed through the viewing area at a background on the opposite side of the box. These backgrounds match the reflectivity of the particles to be separated. Background slides of varying shades are readily exchangeable to give different selectivity for any required separation. As the particles fall through the optical box assembly, each passes through the center of a four-lens, wide-angle viewing system and receives a complete surface inspection on all sides. Any pieces whose color or shade differs from the set standard for one reason or another (too little or too much color content, stains, rock inclusions) cause a change in output voltage in at least one of the photomultipliers. This signal is amplified by an electronic circuit and is used to trigger a short-blast compressed air jet that deflects the unwanted fragment into a reject chute. To ensure that the rejection air blast does not blow dust on the lens system, the ejection does not operate until the product has cleared the optical zone (i.e., a free fall of 3 in.). All the light sources and optical components are kept clear of dust particles by a low pressure air curtain.

Sortex manufactures three models of optical sorters having capacities up to 50 tons per hr. Particle sizes that can be accommodated range from ¼ to 6 in. It is required that close control of sizing be exercised to maximize separating efficiency. Major characteristics and capital costs have been summarized (Table 20).

TABLE 20

CHARACTERISTICS AND CAPITAL COSTS OF SORTEX SEPARATORS

Model	Typical throughput (tons/hr)	Particle size (in.)	Capital cost
621 M	1–2½	¼–¾	$12,460
711 M	2–8	¾–2	27,900
811 M	30–50	2–6	60,800

Performance characteristic curves for the Model 621 M separators apply to a fully liberated material having a specific gravity of 2.7 (Figure 43). It is reported that these curves were obtained by separating dark particles from a feed mixture consisting of light and dark colored granite.

Curves of total processing costs for optical sorting, based upon data provided by Sortex, are presented (Figure 44).

Optical sorting has not been applied to solid waste processing, but potential applications such as the separation of dirt from glass may have merit because of the relatively low overall processing cost.

Another form of optical sorting was developed by Battelle for the removal of dark impurities from rock salt and combines a thermoadhesive process with optical phenomena.[23,24] The process effects a separation by selective radiant heating of the impurities on a heat-sensitive surface such that the dark impurities become warmer and adhere preferentially to the surface thereby effecting a separation. The process worked satisfactorily for the beneficiation of rock salt, and potential applications in solid waste processing might be for the recovery of rubber and plastics.

INERTIAL SEPARATION

The use of inertial forces to effect the separation of solid waste materials is a concept that has received much discussion, but has not been implemented successfully. There are three conceptual types of inertial separators—ballistic, secator, and inclined conveyor (Figure 45). The ballistic separator effects a separation based upon size (i.e., air resistance) and density (i.e., gravity effects). The secator depends on the elastic properties of the materials being separated. The inclined conveyor depends on both density and elastic properties. Although it has been reported that inertial separators are used in European compost systems, attempts to locate installations and operating experiences were not successful during this study.[25] The first known attempt in the United States to employ inertial type separation in the recovery of solid waste is at the Gainesville, Florida, demonstration project compost plant. The device, a "jet slinger," cost approximately $16,000 to fabricate, including motors, drives, etc.[26] As of this writing, serious operational problems had been encountered during initial shakedown trials of the plant, and further use of the jet

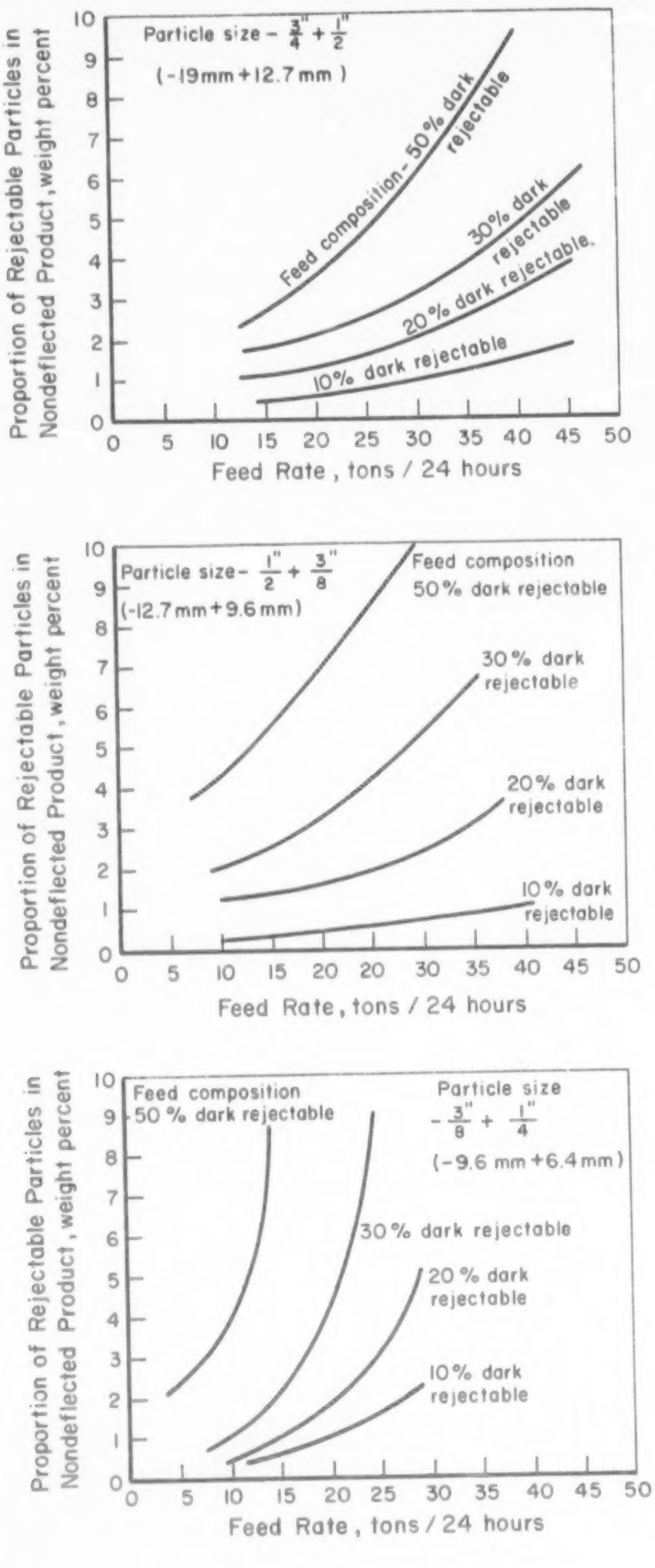


FIGURE 43. *Performance of Model 621M Sortex optical separator. (Source: Sortex Company of North America.)*

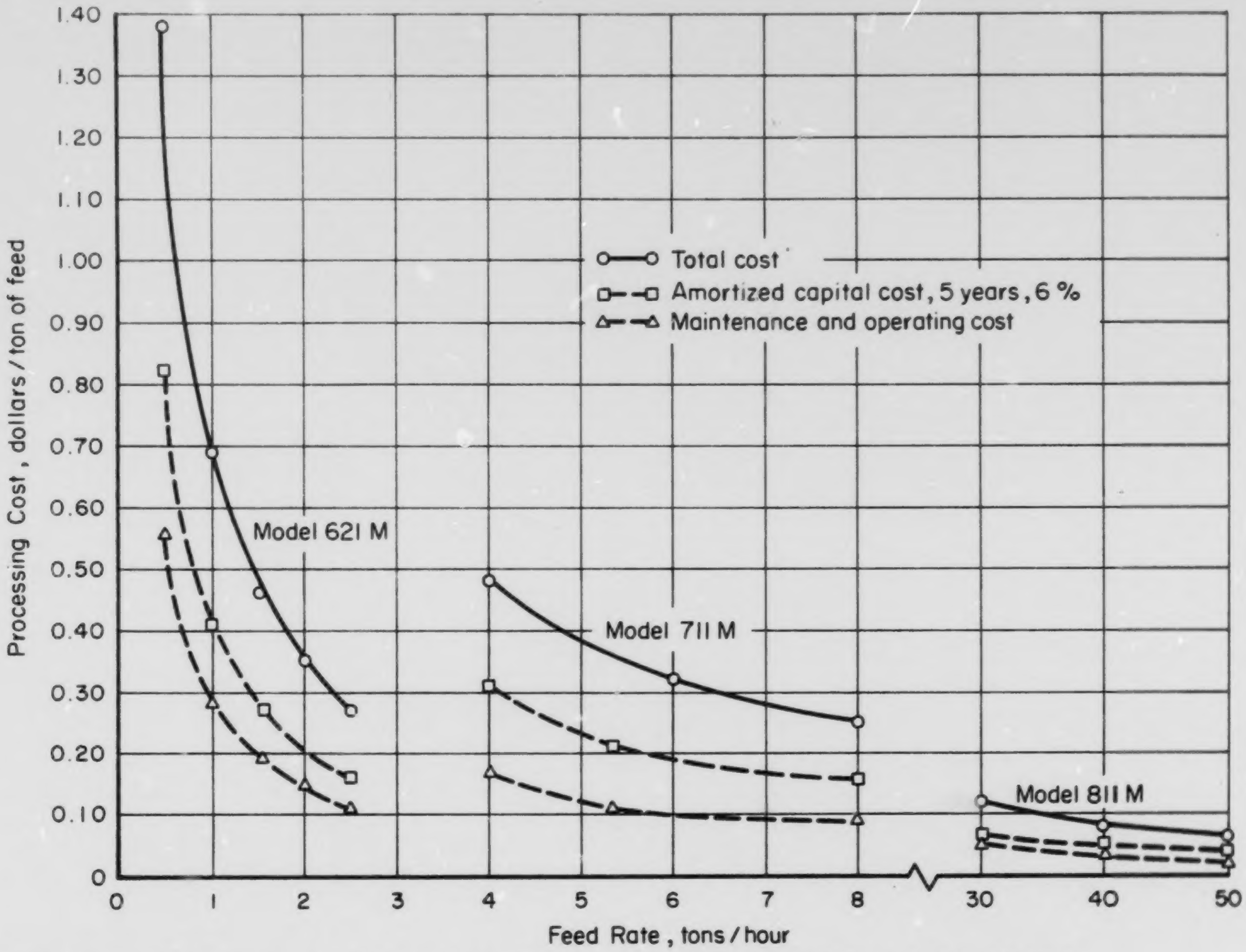


FIGURE 44. *Total processing cost for Sortex optical separators. Specific gravity of material=2.7. (Data provided by Sortex Company of North America.)*

slinger has been discontinued.[37] Inertial separation therefore has not been successfully applied to the separation of solid waste.

FINDINGS

This study not only collected and analyzed cost and performance data for the various recovery processes, but also sought to identify potentially attractive process combinations. In order to determine these combinations, it is necessary to have information not only on the cost and performance of individual processes, but also on their effects upon one another. Unit process characteristics and costs for various mechanical separation methods have been discussed in preceding sections. This section will concentrate upon data gaps related to cost and performance characteristics and the synergistic and antagonistic effects among various size-reduction and separation processes.

DATA GAPS

Preceding discussions have indicated a considerable lack of reliable data concerning performance and cost of mechanical separation techniques for the processing and recovery of solid waste. As indicated, applications of mechanical separation of solid waste processing and recovery are currently limited and involve only the use of magnetic separation for tin can recovery, vibrating screens for size clarification, and gravity separation by air-flotation stoners to remove glass from compost. This study demonstrated that none of the existing installations had reliable performance and cost data, nor were they collecting it.

Magnetic separation data is needed on performance and on the efficiency of removing ferrous materials from mixed solid waste. Relationships that need to be investigated include the effect of particle size and ferrous content of the mixed waste on removal efficiency and separator capacity.

No eddy current separation data are available other than that reported by one company whose experience seems to indicate little potential for applications of eddy phenomena to the separation of nonmagnetic, conductive materials from solid waste.* Controlling the particle size of the input to an eddy-current separator by use of screening might eliminate some problems, but would not do much for the control of shape and other factors. It may be worth investigating, however, since the relative effects of these variables have not been defined.

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*Eriez Manufacturing Company, Asbury Road at Airport, Erie, Pennsylvania.

Because of this high sensitivity of gravity separation devices to particle size in solid waste recovery systems, size classification will be an essential element. Dry size classification is accomplished in various industrial applications by vibrating screens. Dry size classification in the processing and recovery of solid waste can be effected by similar systems. However, performance data are available only for specialized industrial applications such as in minerals beneficiation. Current applications of screening in solid waste processing are limited to the preparation of compost for processing in stoners to remove glass. However, it is not considered likely that data will become available from these applications. The addition of screening and stoning operations to the Bureau of Solid Waste Management demonstration compost planting in Gainesville, Florida, would provide an excellent opportunity to collect some basic process data, not only on glass removal, but also on the removal of plastic, nonferrous metals, and other materials.

In the area of wet processing, and specifically wet classification, spiral classifiers need to be investigated for the recovery of relatively dense, small particles such as those found in incinerator residues. Investigators of this area should be aware of studies being conducted by the U.S. Bureau of Mines in connection with their work on the salvage of municipal incinerator residues.

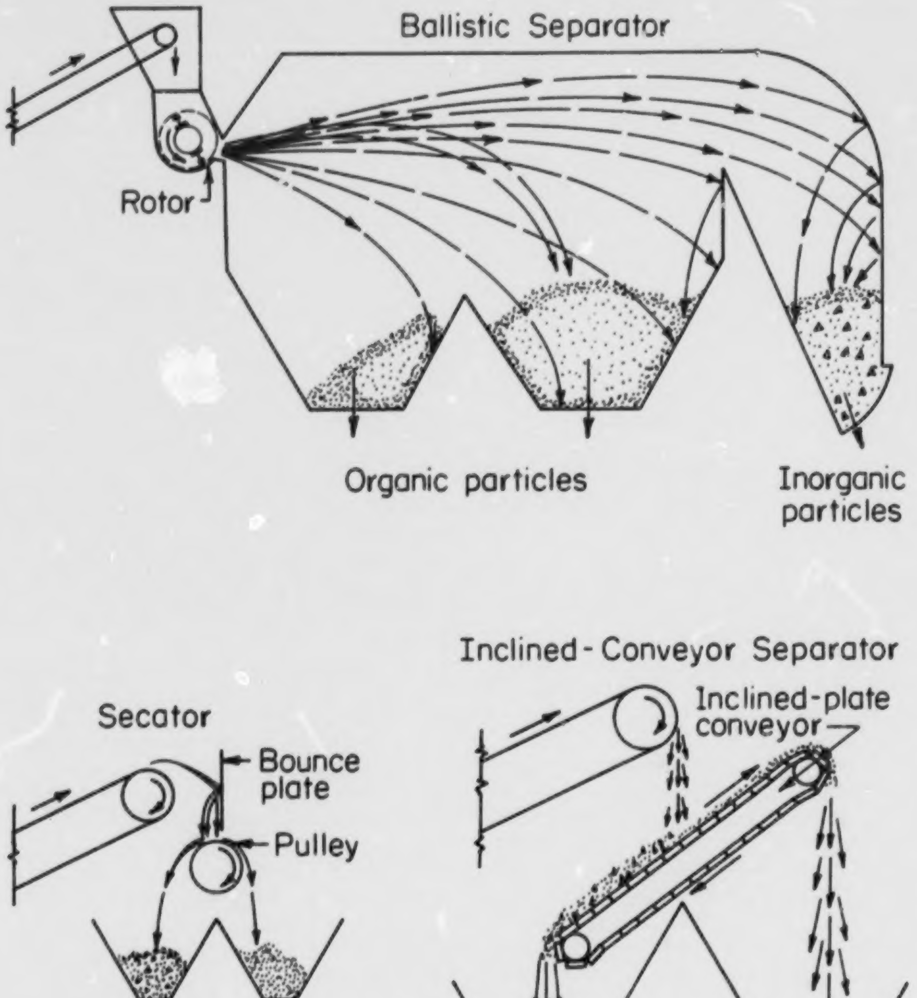
Ballistic Separator
Rotor
Organic particles
Inorganic particles
Inclined-Conveyor Separator
Inclined-plate conveyor
Secator
Bounce plate
Pulley
Heavy and resilient particles
Light and inelastic particles
Heavy and resilient particles
Light and inelastic particles

FIGURE 45. *Types of inertial separators. (From Wiley, John S. Some specialized equipment used in European compost systems.* Compost Science, *4(1):10, Spring 1963.)*

Perhaps one of the largest unknown areas and one with several potential applications to solid waste recovery is flotation and its companion process, dense media separation. As indicated in earlier discussions, the variables determining process cost and performance for flotation range over several orders of magnitude. Experimental studies should be conducted to establish critical factors for making several cuts on mixed solid waste and component cleanup. The studies being conducted by the U.S. Bureau of Mines should generate flotation and dense media separation data for the recovery of incinerator residues. Additional work is needed, however, to explore the possibility of separating organics, cellulosic components, nonferrous metals, glass and other suitable input materials for the by-product recovery processes. But it must be emphasized that the first requirement is to determine the feasibility of these separations and then to obtain cost and performance measurements.

There is a universal lack of unit process cost and performance data for the application of mechanical separation techniques to solid waste recovery. The specific data of interest concerns the interrelationship between particle size and distribution in the feed stream, throughput or capacity, processing cost, and separation efficiency. The lack of data stems from a lack of application of the techniques and from the failure to collect data in the few applications that do exist. Determining which data voids are the most critical requires an assessment of the attractiveness of various overall process combinations. This will be discussed following a review of recovery and utilization process technology.

In addition to unit process cost and performance data, there is also a need for acceptable standardized cost allocation procedures so that unit process costs can be established and compared on a meaningful basis. A significant fraction of total product cost is related to auxiliary items (i.e., materials handling equipment, structures, etc.). Therefore, the sum of the unit costs of the functional equipment items may not adequately represent the entire

TABLE 21

SYNERGISTIC AND ANTAGONISTIC EFFECTS RELATIVE TO PARTICLE SIZE FOR SIZE-REDUCTION AND SEPARATION PROCESSES

DRY PROCESSING	
Size reduction	Nominal output particle size capability—range
Crushers	½–10 in.
Cage disintegrators	Powder–½ in.
Shears	1–4 ft
Shredders	4–6 in.
Rasp mills	<2 in.
Drum pulverizers	<2 in.
Disk mills	Fine powder
Hammermills	1–6 in.
Separation	Approximate nominal input particle size required—range
Magnetic separation	<8 in.
Vibrating screens	⅛–3 in.
Stoners	1/16–2 in.
Osborne separator	1/64–3/16 in. (organic fraction) 3/16–1 in. (inorganic fraction)
Optical sorting	¼–6 in.
WET PROCESSING	
Size reduction	Nominal output particle size capability—range
Disk mills	Pulp
Wet pulpers	Fine Fibers–1 in.
Separation	Approximate nomimal input particle size required—range
Spiral classifiers	200 mesh (0.0024)–¼in.
Flotation	100 mesh (0.0059)–1/16 in.
Dense media	10 mesh (0.066)–3 in.
Wilfley tables	6 mesh (0.132 in.)–150 mesh
Mineral jigs	$<1½$ in.

cost. An example of this was provided in the discussions of magnetic separation. Similar problems are encountered in the cost analyses for the recovery systems, but are less pronounced since the data on total recovery systems include the costs of auxiliary equipment. In the area of separation equipment, however, auxiliary cost items must be defined and allocated to the respective process so that meaningful overall unit process costs can be developed.

SYNERGISTIC AND ANTAGONISTIC EFFECTS

Key factor in the selection of attractive process combinations is the synergistic and antagonistic effects between performance characteristics and operating features of the various unit processes. These effects may be discussed in terms of trade-offs between those size-reduction and separation processes which are principally related to particle size output-input compatibility. These trade-offs are discussed in qualitative terms since sufficient information is not available, especially as relating cost and performance characteristics of separation processes as a function of particle size.

In terms of compatibility with separation processes, two general categories of size-reduction equipment may be defined—wet and dry systems. Dry size-reduction systems are more flexible, permitting either wet or dry operations downstream. Once a wet size-reduction system is selected, one is limited to consideration of wet separation systems unless drying is provided. On the basis of existing experience with solid waste recovery, it is difficult to justify the high drying costs which would be incurred.

In a wet system, sizing would probably be accomplished best in spiral classifiers, even though these have not as yet been applied to solid waste processing. Potential applications would be in preparing feed material for Wilfley tables, mineral jigs, and flotation operations; all these require a relatively small particle size. Wet screening, as previously mentioned, does not hold much promise for solid waste processing because the generally soft nature of mixed solid waste would tend to promote screen clogging.

Except for the wet versus dry considerations, sufficient information is not available to determine the best type of size-reduction equipment for preparing feed to a given separator. Nevertheless, some general observations can be made relating size-reduction equipment output capabilities to separator input requirements (Table 21 and Figure 46). Particle size output-input compatibility, however, is not the only factor in determining overall process combinations. Other critical factors are the type of material being processed and the freedom of the individual components. It should also be noticed that reduction to small particle sizes would be accomplished in several stages because of the constraints on the size of input to the various size-reduction equipment. In addition, manufacturers' experience indicates that most efficient particle size reduction is accomplished in stages.

Another type of synergistic effect relates to a possible phenomenon concerning different degrees of particle size reduction for different materials. Certain observations indicate that different materials in mixed solid waste are reduced to different sizes when processed in a hammermill (Figure 10). Thus, size reduction followed by screening might constitute a basis for effecting a separation of different materials.

Synergistic and antagonistic effects may also be defined among the various separation processes themselves. These definitions are of interest since any complete solid waste recovery system is likely to contain several parallel and sequential separation processes, and compatible outputs of one process and input requirements of another are essential. This is especially true for the various gravity separation methods that require close control of particle size input to effect efficient gravity separation. Input particle size control may also be one technique for achieving improved performance of eddy current separation techniques.

Data do not exist for defining cost-benefit trade-offs between increased costs associated with screening and size reduction to yield a fine particle stream and benefits in terms of increased performance of the separation process which would be associated with the finer particles.

Dry Size Reduction Followed by Dry and/or Wet Separation

Separation / Dry Size Reduction	Dry					Wet				
	Magnetic Separation	Vibrating Screens	Stoners	Osborne Separator	Optical Sorting	Spiral Classifiers	Flotation	Dense Media	Wilfley Tables	Mineral Jigs
Crushers	+	+	–	–	+	–	–	–	–	+/–
Cage Disintegrators	+	+	+	+	+	+	+	+	+	+
Shears	–	–	–	–	–	–	–	–	–	–
Shredders	+	+/–	–	–	–	–	–	–	–	–
Rasp Mills	+	+	+	+/–	+	+/–	+/–	+/–	–	+
Drum Pulverizers	+	+	+	+	+	+	+	+	–	+
Disk Mills	–	–	–	–	–	+	+	+	+	+
Hammer Mills	+	+	+	+	+	–	–	–	–	+/–

Wet Size Reduction – Wet Separation

Separation / Size Reduction	Spiral Classifiers	Flotation	Dense Media	Wilfley Tables	Mineral Jigs
Disk Mills	+	+	+	+	+
-Wet Pulpers	+	+	+	+/–	+/–

LEGEND

+	Generally compatible
+/–	Marginal due to considerations regarding materials and physical liberation or other factors
–	Incompatible

FIGURE 46. *Summary of compatibility of size-reduction output, particle-size capabilities, and separation process particle-size requirements.*

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VI. Recovery and utilization

RECOVERY AND UTILIZATION of solid waste encompass two general concepts: recovery by conversion and recovery by salvage. Conversion involves the chemical, biological, or physical processing of waste components to produce new by-products. Salvage connotes recovery of waste components in their original form, i.e., recovery of tin cans to produce steel, or recovery of newsprint for manufacture into other paper products. Conversion processes investigated during this study were composting, incineration and waste heat recovery, pyrolysis, hydrolysis, and fermentation. Within the general context of separation and salvage the following materials were investigated: tin cans, paper, plastics, glass, fly ash, and incinerator residues.

The ultimate motivation for size reduction and separation of solid waste is to make possible various recovery schemes. Each technique requires a different degree and type of preprocessing in terms of size reduction and separation. The extent to which these requirements can be established based upon existing operating experience is discussed below

As has been indicated, this study emphasized the collection of cost and performance data. Since recovery processes are, for the most part, more related to the end product, and, hence, the economics of solid waste recovery, proprietary limitations constrained availability of data more than was the case for size-reduction or separation equipment. This constraint was further compounded by the marketing philosophy of many companies currently engaged in solid waste recovery, in that they do not wish to sell equipment or processes, but, rather, are interested only in selling a disposal service to municipalities. Consequently, equipment and process costs and system capabilities are closely guarded as proprietary secrets.

COMPOSTING CONVERSION PROCESSES

Composting is the solid waste recovery technique for which the greatest amount of data are available. This information pertains primarily to complete plants and covers size reduction, separation, and salvage as well as the compost process itself.

Compost is a humus-like material which results from the aerobic biological stabilization or digestion (at temperatures of 150 to 170 F) of the biodegradable (organic) materials in solid waste. Aerobic conditions are essential in order to minimize odor problems and to ensure sufficiently rapid, and hence economic, processing times. Because of the difficulty of separation, a considerable amount of nonbiodegradable material is typically passed through the digestion process and emerges essentially unchanged.

The primary attributes of compost are those of a soil conditioner. In this role, compost will: (1) improve soil structure, (2) increase moisture holding capacity, (3) reduce leaching of soluble inorganic nitrogen, (4) increase the phosphorus availability to growing plants, and (5) increase buffering capacity of the soil. It should be emphasized that compost is not a fertilizer. It contains only 1 percent or less of each of the major fertilizer nutrients—nitrogen, phosphorus, and potassium. Thus, only a limited market exists for compost and the economics of a given operation are highly sensitive to market limitations. It is clear that the future for compost as a soil conditioner alone is not bright. Peat moss is the major form of soil conditioner utilized in the United States today. In 1966, slightly in excess of 600,000 tons were consumed.[28] The solid waste from a city with a population of about

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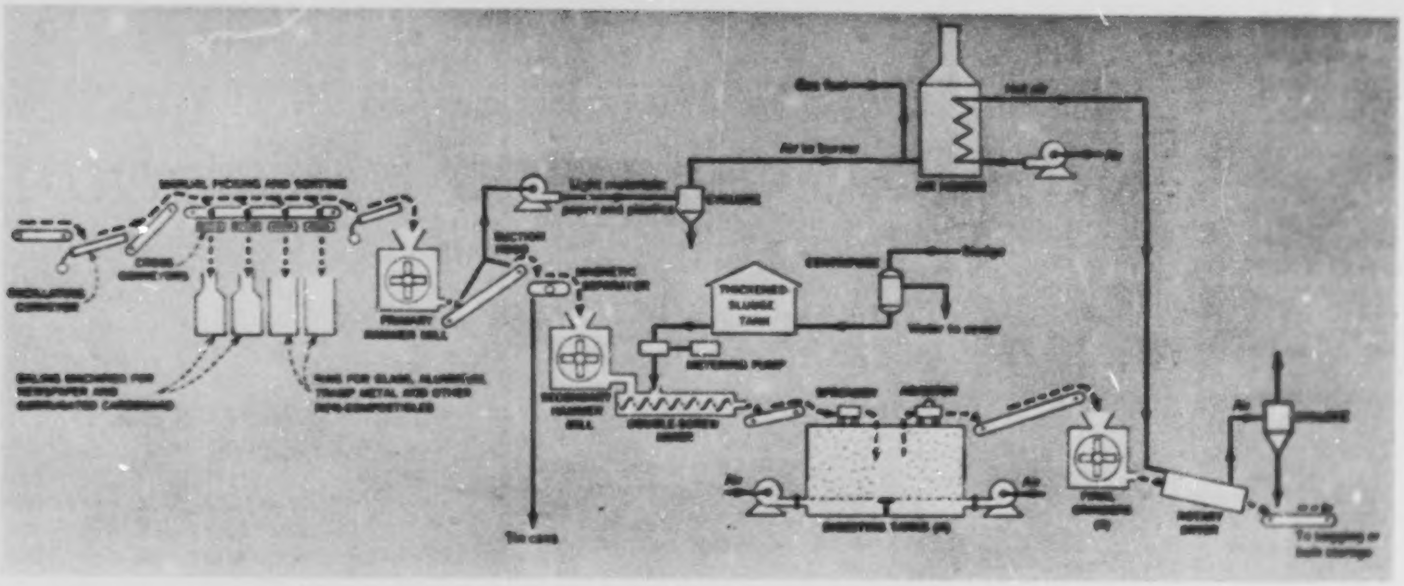
Manual picking and sorting
Oscillating conveyor
Cross conveyors
Baling machines for newspaper and corrugated cardboard
Bins for glass, aluminum, tramp metal and other non-compostables
Primary hammer mill
Suction hood
Light materials paper and plastics
Cyclone
Gas fuel
Air to burner
Hot air
Air heater
Air
Magnetic separator
Tin cans
Thickened sludge tank
Centrifuge
Sludge
Water to sewer
Metering pump
Secondary hammer mill
Double screw mixer
Spreader
Agitator
Air
Digesting tanks (4)
Air
Final grinders (2)
Rotary dryer
Air
To bagging or bulk storage

FIGURE 47. *Basic Metro process as indicated in the schematic flow diagram of the Lone Star Organics, Inc., compost plant, Houston, Texas.* (*From* Chemical Engineering, *Nov. 6, 1967. Reprinted with permission.*)

800,000 could produce this much compost in a year's time. The merits and economics of compost should be evaluated in new terms, for example, as an organic base for the manufacture of chemical fertilizer. Failure to understand this point has contributed to rather unsuccessful management and promotion of several composting operations during the last several years in the United States.

Recently there has been much documentation of composting technology and its successes and failure.[29,30] This information is not repeated here; only enough background information is provided to render the cost and performance data meaningful.

In addition to manufacturing, compost plants have traditionally engaged in salvage operations. Most systems employ various types of size reduction, and separation of materials such as tin cans, newsprint, rags, and glass, which are removed for their salvage value and to upgrade the quality of the compost produced. Most existing plants operate under contract with municipalities served with service charges of $3 to $4 per ton of refuse accepted.

Major U.S. composting systems are of two types, depending on the type of digestion employed. The first and most common type involves mechanical digestion with retention of the material in a bin, tank, or other similar type of digester for about 5 days. During this period, the waste is agitated and air is introduced to maintain aerobic conditions. The second type, adapted largely from European practice, involves piling the compost out-of-doors for several weeks in windrows several hundred ft long, about 6 to 10 ft wide at the base, and 3 to 5 ft high. During this period the material in the windrows is turned or otherwise agitated once or twice per week. After digestion in windrows and sometimes even after mechanical digestion, the compost is "cured" in windrows for an additional 2 to 3 weeks. Actual curing mechanisms are not well established, but it is believed that the more resistant cellulosic materials are broken down at this time. Some other change also occurs, for it has been observed that cured compost does not seem to inhibit plant growth, whereas uncured compost usually does. This effect is unlikely to be dependent on cellulose breakdown alone.

Of the two methods, mechanical digestion appears to hold the most promise, especially for large composting systems in urban centers where the bulk of the solid waste is generated. In agricultural and rural areas where land is available and where odor problems are not critical, the windrow system may have advantages. Odor problems are a definite consideration since it is somewhat more difficult to maintain aerobic conditions in the windrow system than in mechanical systems.

RECENT AND CURRENT APPLICATIONS OF COMPOSTING

In 1967 and 1968, six companies or organizations had experience in large-scale composting of municipal solid waste; each employing a somewhat different system. They are as follows: (1) Metropolitan Waste Conversion Corporation, Wheaton, Illinois; (2) International Disposal Corporation, St. Petersburg, Florida; (3) Fairfield Engineering Company, Marion, Ohio; (4) United Compost Services, Inc., Houston, Texas; (5) Gruendler Crusher and Pulverizer Company, St. Louis, Missouri; and (6) Tennessee Valley Authority Composting Plant, Johnson City, Tennessee (joint venture with U.S. Public Health Service). The systems and operations of each of these organizations are discussed below with cost data, to the extent they were available.

METROPOLITAN WASTE CONVERSION CORPORATION (METRO)

Metro entered the composting field in 1963 with a small 50-ton-per-day pilot plant in Largo, Florida. Based upon experience at Largo, a 360-ton-

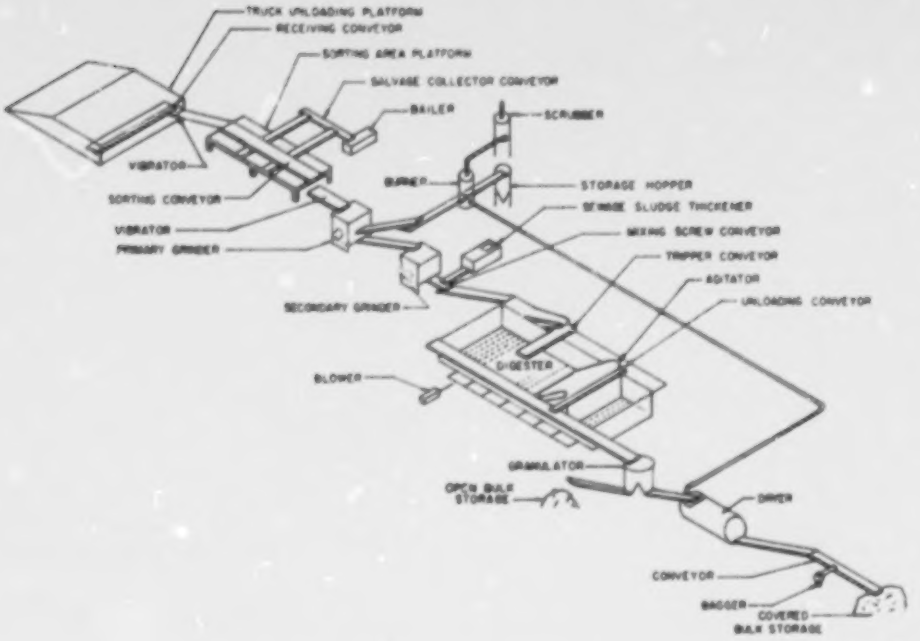
TRUCK UNLOADING PLATFORM
RECEIVING CONVEYOR
SORTING AREA PLATFORM
SALVAGE COLLECTOR CONVEYOR
BAILER
SCRUBBER
VIBRATOR
SORTING CONVEYOR
BURNER
STORAGE HOPPER
SEWAGE SLUDGE THICKENER
VIBRATOR
PRIMARY GRINDER
MIXING SCREW CONVEYOR
TRIPPER CONVEYOR
AGITATOR
UNLOADING CONVEYOR
SECONDARY GRINDER
DIGESTER
BLOWER
GRANULATOR
OPEN BULK STORAGE
DRYER
CONVEYOR
BAGGER
COVERED BULK STORAGE

FIGURE 48. *Schematic flow diagram of the Gainesville Municipal Waste Conversion Authority, Inc., compost plant, Gainesville, Florida. (From Harding, C. I. Recycling and utilization. In Proceedings; the Surgeon General's Conference on Solid Waste Management for Metropolitan Washington, July 19–20, 1967. Public Health Service Publication No. 1729. Washington, U.S. Government Printing Office, 1967. p. 105–119.)*

per-day plant was built in Houston, Texas, and has been operating successfully since January 1967, under the name of Lone Star Organics, Inc. The Metro system is also being employed in a 150-ton-per-day Bureau of Solid Waste Management demonstration project in Gainesville, Florida, which began operation early in 1968.

The basic Metro process, as installed in Houston and Gainesville, involves sorting and salvage, two stages of size reduction, sewage sludge addition, digestion, and final product preparation (Figures 47 to 50).

As indicated previously, the major difference in composting schemes is in the digestion process. Material delivered to the digesters by a conveyor is moved longitudinally by an agitator on which a track mixes the compost about once a day. Digester retention time is about 5 days, after which the compost is conveyed to the final processing.

Another unique feature and recent addition to the Houston plant, as mentioned previously, is the use of a Mark IV, Sutton, Steele, and Steele air-float stoner to remove glass from the final compost product.

Capital costs for the Houston and Gainesville plants were $1.7 and $1.25 million, respectively, somewhat higher than the general trends exhibited by

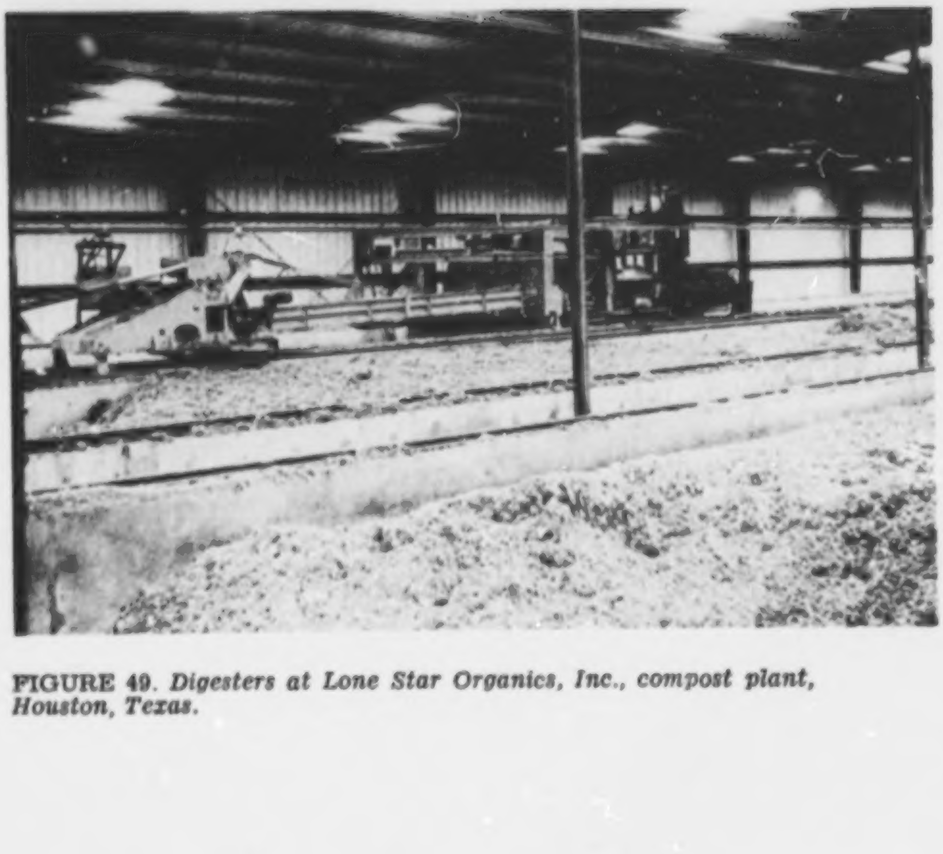

FIGURE 49. *Digesters at Lone Star Organics, Inc., compost plant, Houston, Texas.*

the other data because of the experimental and prototype nature of these plants (Table 22).

INTERNATIONAL DISPOSAL CORPORATION (IDC)

In July 1966, IDC began operation of a 105-ton-per-day compost plant employing the Naturizer process in St. Petersburg, Florida. The system design is based upon pilot tests conducted by Salvage and Conversion Systems Corporation (SACS) in the early 1960's at San Fernando, California, and Norman, Oklahoma. IDC was formed from a recapitalization of SACS, the All State Insurance Company, and the Westinghouse Electric Corp. Size reduction, handsorting, and magnetic separation is accomplished in a fashion similar to that employed by the Metro system (Figure 51).

The unique feature of the Naturizer system is the digestion process consisting of five stacked conveyors. After size reduction, separation, and addition of water to raise the moisture content, the material is delivered to the digester where it is stacked to a depth of about 6 ft on the continuous conveyors. These conveyors are about 9 ft wide and about 150 ft long. On the average of once a day, material is dumped or transferred to a lower conveyor where a fan supplies air to the compost. Early in 1968, the St. Petersburg plant was reported temporarily closed due to odor problems.[31] These conditions may have been due largely to the limited amount of air supplied by the aeration system which would in turn lead to the development of anaerobic conditions and associated odors.

Capital cost of the St. Petersburg plant was $1.5 million. Capital costs for other capacities of the system design were estimated and summarized (Table 23).

FAIRFIELD-HARDY PROCESS

The Fairfield Engineering Company uses the Fairfield-Hardy composting system (Figure 52). Operational experience with this system is limited to a 25-ton-per-day plant in Altoona, Pennsylvania. Waste material processed by the plant is a portion of the garbage collected by the city; Altoona has separate garbage and rubbish collection. As of this writing, construction is underway for a 300-ton-per-day Fairfield-Hardy system in San Juan, Puerto Rico.

In the Fairfield-Hardy digester, material is fed through the top center and is distributed to the outer cir-

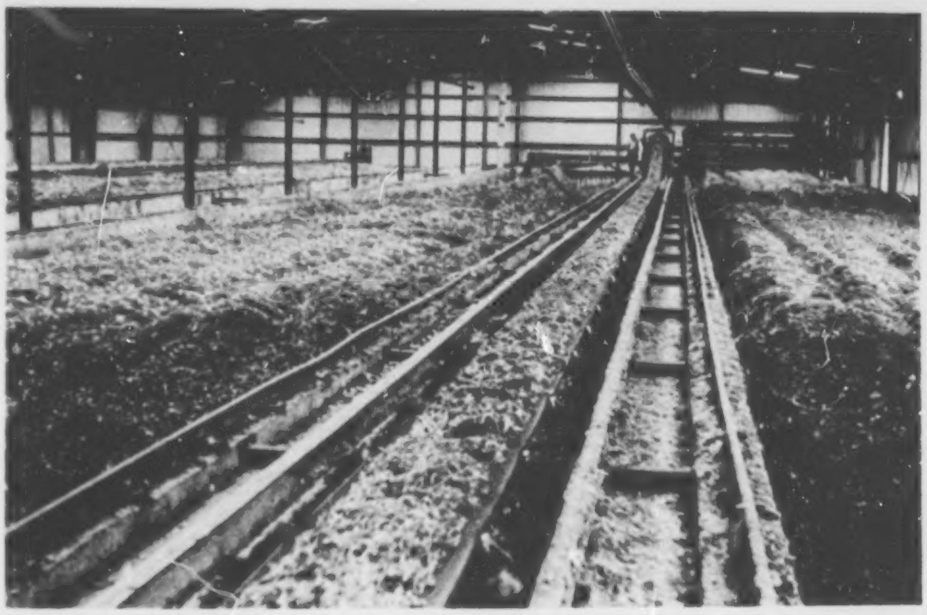

FIGURE 50. *Mixing of compost in digesters at Lone Star Organics, Inc., compost plant, Houston, Texas.*

TABLE 22

ESTIMATES OF CAPITAL COSTS, ENERGY, AND LABOR REQUIREMENTS FOR METRO COMPOST SYSTEMS

Capacity (tons/day)	Capital cost (dollars)	Power requirements (hp)	Labor requirements (men)
100	*900, 000	*1, 250	*12
150 (Gainesville)	†1, 250, 000	†1, 100	-----
200	*1, 200, 000	*1, 700	*17
300	*1, 500, 000	*1, 900	*25
360 (Houston)	‡1, 700, 000	-----	-----
400	*1, 600, 000	*2, 000	*30

*Harding, C. I. Recycling and utilization. *In* Proceedings; the Surgeon General's Conference on solid waste management for Metropolitan Washington, July 19–20, 1967. Public Health Service Publication No. 1729. Washington, U.S. Government Printing Office, 1967. p. 115.

†Personal communication from H. W. Houston, Project Director, Gainesville Municipal Waste Conversion Authority, Inc., Aug. 8, 1967.

‡Personal communication from G. Vaughn, Plant Manager, Lone Star Organics, Inc., Aug. 8, 1967.

TABLE 23

ESTIMATES OF CAPITAL COSTS, ENERGY, AND LABOR REQUIREMENTS FOR IDC-NATURIZER COMPOST SYSTEMS

Capacity (tons/day)	Capital cost (dollars)	Power requirements (hp)	Labor requirements (men)
100	*1, 400, 000	*600	*20
105	†1, 500, 000	-----	-----
200	*2, 100, 000	*800	*28
300	*2, 700, 000	*950	*36
400	*3, 200, 000	*1, 100	*45

*Harding, C. I. Recycling and utilization. *In* Proceedings; the Surgeon General's Conference on Solid Waste Management for Metropolitan Washington, July 19–20, 1967. Public Health Service Publication No. 1729. Washington, U.S. Government Printing Office, 1967. p. 105–119.

†Personal Communication from R. Lynn, Plant Manager, IDC, St. Petersburg, Florida, Aug. 1967.

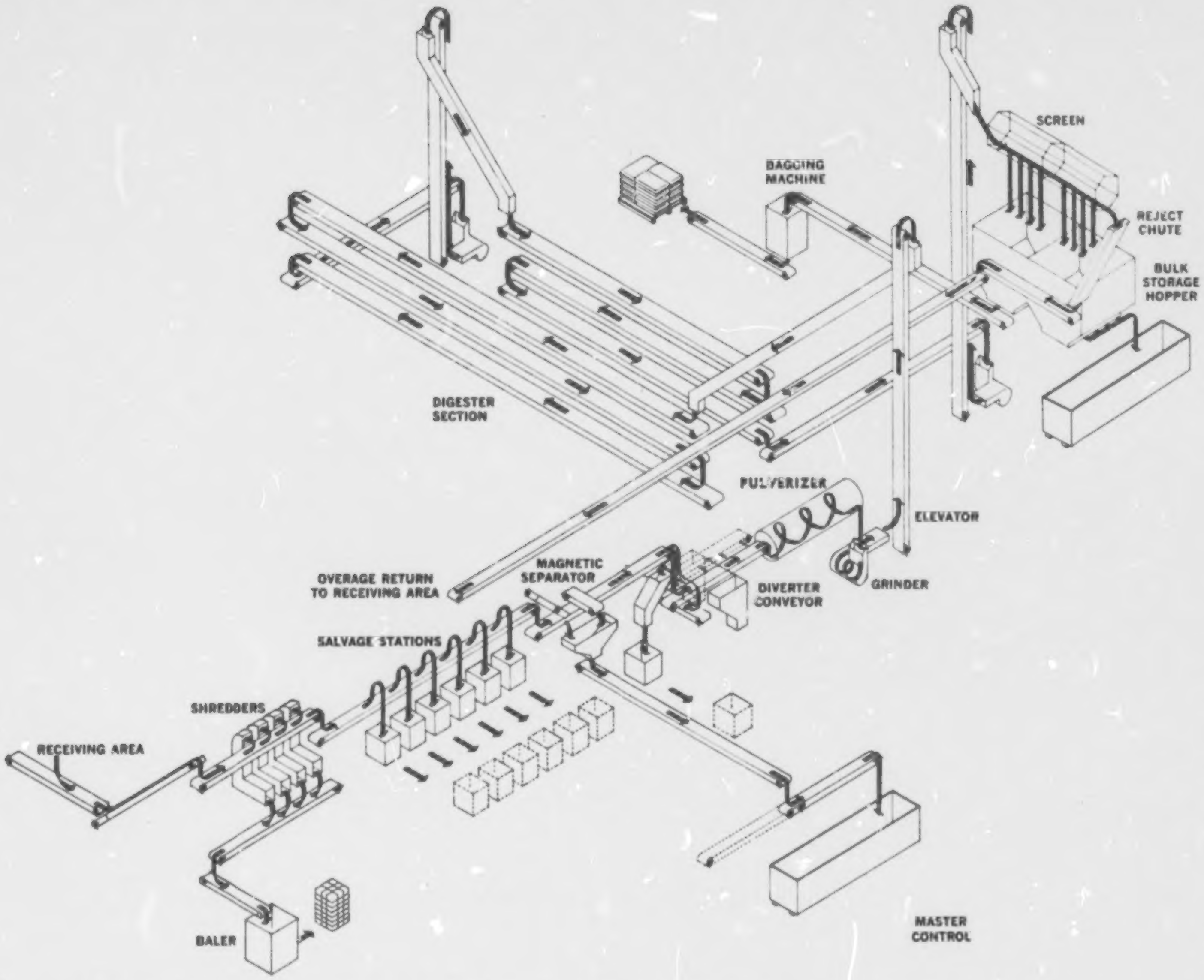
SCREEN
BAGGING MACHINE
REJECT CHUTE
BULK STORAGE HOPPER
DIGESTER SECTION
PULVERIZER
ELEVATOR
GRINDER
DIVERTER CONVEYOR
MAGNETIC SEPARATOR
OVERAGE RETURN TO RECEIVING AREA
SALVAGE STATIONS
SHREDDERS
RECEIVING AREA
BALER
MASTER CONTROL

FIGURE 51. *Schematic flow diagram—IDC–Naturizer Compost Plant, St. Petersburg, Florida.* (*Source: International Disposal Corporation.*)

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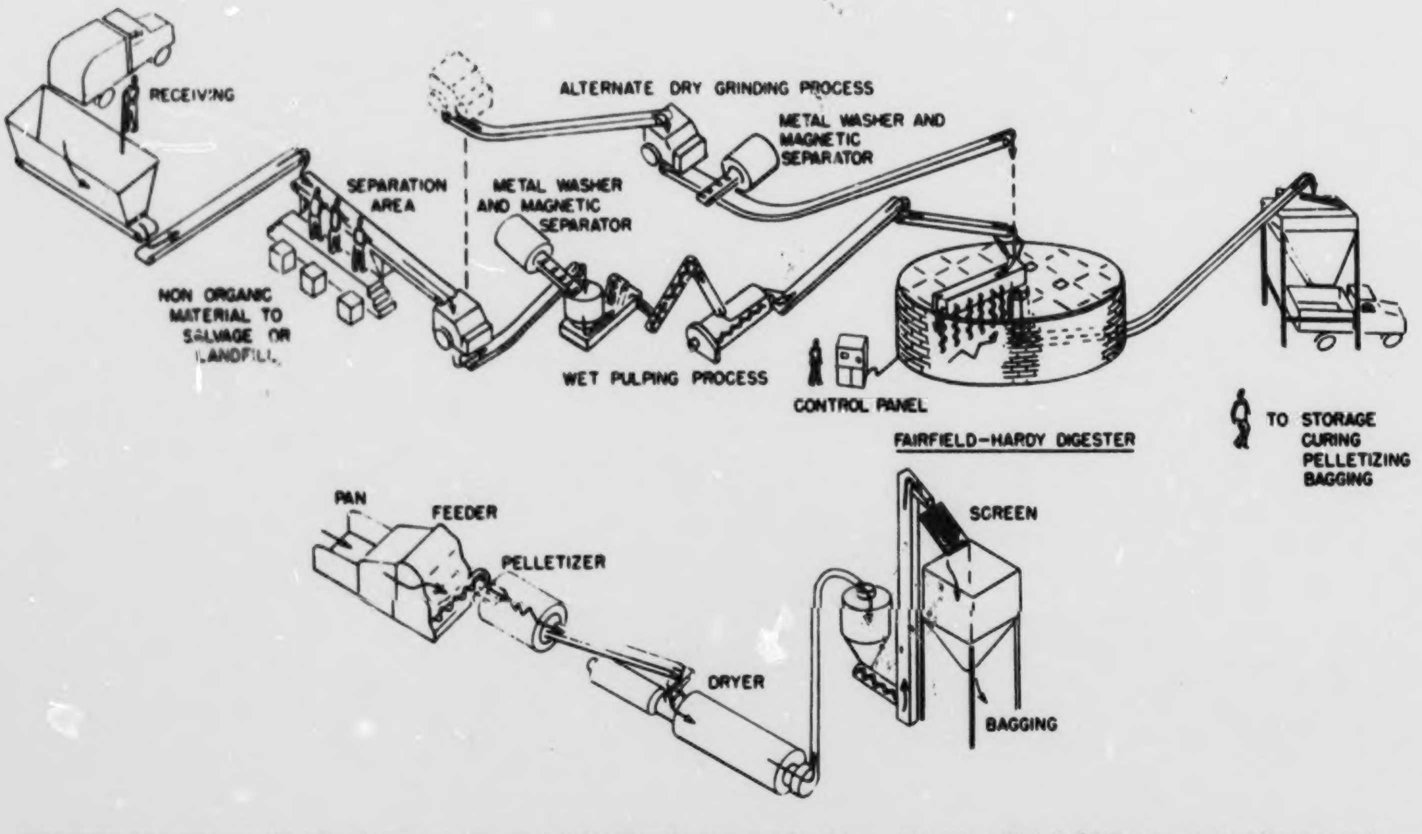
RECEIVING
NON ORGANIC MATERIAL TO SALVAGE OR LANDFILL
SEPARATION AREA
METAL WASHER AND MAGNETIC SEPARATOR
ALTERNATE DRY GRINDING PROCESS
METAL WASHER AND MAGNETIC SEPARATOR
WET PULPING PROCESS
CONTROL PANEL
FAIRFIELD-HARDY DIGESTER
TO STORAGE CURING PELLETIZING BAGGING
PAN
FEEDER
PELLETIZER
DRYER
SCREEN
BAGGING

FIGURE 52. *Schematic flow diagram for Fairfield-Hardy compost system. (Source: Fairfield Engineering Company.)*

cumference of the tank by a rotating distributor bridge. Attached to the rotating bridge are nine augers that periodically agitate the material in the digester, gradually working it toward the center where it is discharged through the bottom of the digester (Figure 53). Retention time in the digester is about 5 days.

Another unique feature of the Fairfield-Hardy system is the size reduction process. Wet pulping followed by dewatering is employed, as opposed to dry grinding in a hammermill. There is a dry grinder at the Altoona plant, but its use is largely experimental. Although the cost figures indicate this to be a rather expensive process (Tables 24 and 25), an extremely high-quality product results.

An air-float stoner has been added

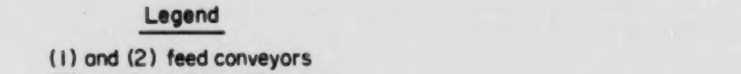
Legend
(1) and (2) feed conveyors
(3) rotating bridge with augers
(4) standpipe for discharge
(5) discharge conveyor
(1)
(2)
(3)
(4)
(5)

FIGURE 53. *Fairfield-Hardy digester. (Sources: Fairfield Engineering Company.)*

TABLE 24

ESTIMATES OF CAPITAL COSTS, ENERGY, AND LABOR REQUIREMENTS FOR FAIRFIELD-HARDY COMPOST SYSTEMS

Capacity (tons/day)	Capital cost (dollars)	Power requirements (hp)	Labor requirements (men)
100	1, 370, 000	930	11
200	2, 000, 000	1, 590	18
300	2, 510, 000	1, 830	25
400	3, 210, 000	2, 560	30

Source: Fairfield Engineering Company.

TABLE 25

ESTIMATES OF PROCESSING COSTS FOR FAIRFIELD-HARDY COMPOST SYSTEMS

Capacity		Operating costs							Amortized capital cost* (excluding land) and interest	Total processing cost
		Payroll		Utilities and supplies		Administration including interest		Total		
(tons/day)	(tons/yr)	($/yr)	($/ton)	($/yr)	($/ton)	($/yr)	($/ton)	($/ton)	($/ton)	($/ton)
100	28, 600	81, 000	2. 83	74, 400	2. 60	145, 800	5. 11	10. 54	2. 41	12. 95
200	57, 200	126, 400	2. 21	141, 700	2. 48	214, 630	3. 76	8. 45	1. 75	10. 20
300	85, 800	172, 400	2. 01	189, 000	2. 21	270, 435	3. 20	7. 42	1. 46	8. 88
400	114, 400	204, 800	1. 79	262, 000	2. 29	336, 750	3. 02	7. 10	1. 40	8. 50

Source: Fairfield Engineering Company.

*Assuming 20-yr life.

recently to the Altoona plant.* Due to the low capacity of the Altoona plant (3 to 4 tons per hr), a laboratory model stoner was found adequate. The heavy fraction from the stoner which is mostly glass has a bulk density of about 73 lb per cu ft. The light compost product has a bulk density of about 39 lb per cu ft.

Estimates of capital costs, energy and labor requirements (Table 24), and of overall processing costs (Table 25) were determined for the Fairfield-Hardy system.

An analysis of the capital costs shows that approximately 30–40 percent of the costs is attributable to the digestion process, and the remainder to auxiliary support facilities (Figure 54).

JOHN R. SNELL PROCESS

In January 1967, United Compost Services in Houston, Texas, put into operation a 300-ton-per-day plant employing a design developed by John R. Snell Engineers, Lansing, Michigan. The system design is a hybrid of the Metro and Fairfield-Hardy systems, with the digester consisting of a large open rectangular concrete tank. After sorting and grinding, the refuse is fortified with sewage sludge and is conveyed to the digester, where oxygen is supplied by pulling air down through the material with large exhaust fans. The material is agitated by means of rotating augers mounted on a bar suspended across the width of the tank, which traverses the tank longitudinally. The rotation of the augers is adjusted so that material is moved across the width of the tank in about 5 days and is discharged at the opposite side.

The United Compost Services Plant operated until April 1967 when a contractual dispute with the city resulted in termination of the operation. As of this writing, the dispute has not been resolved and operation has not resumed.

The Houston plant, which has a capacity of 300 tons per day, cost $1.6 million. Power requirements amount to about 1,700 hp. Attempts to obtain process flow sheets and photographs of the system were unsuccessful, but costs for other plant capacities employing Snell's design range from $2.69 to $3.44 per ton (Table 26).[22]

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*Manufactured by Sutton, Steele, and Steele.

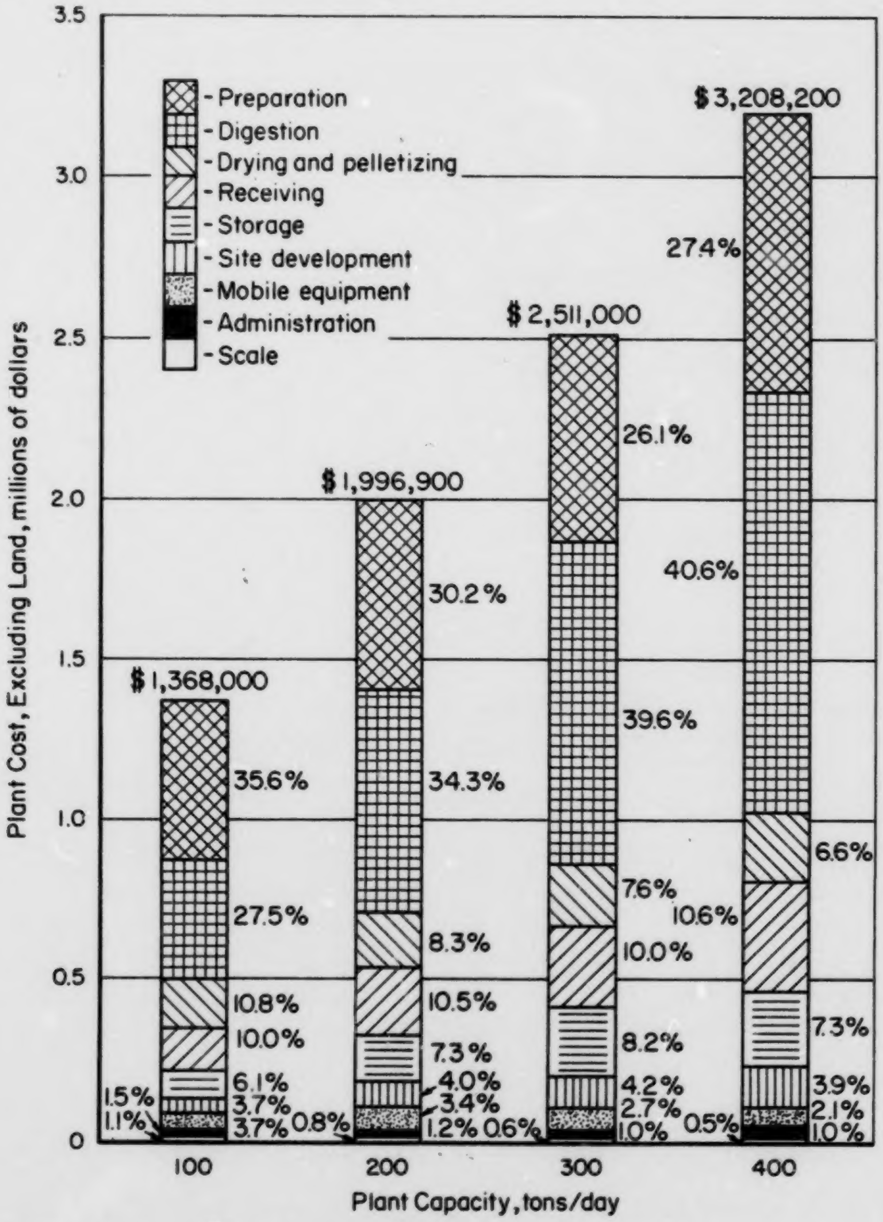

FIGURE 54. *Cost breakdown for Fairfield-Hardy compost systems. (Source: Fairfield Engineering Company.)*

TABLE 26

ESTIMATED CAPITAL AND PROCESSING COSTS FOR COMPOST PLANTS USING THE JOHN R. SNELL COMPOSTING PROCESS

Capacity (tons/day)	Capital cost	Amortization of fixed charges	Operation and maintenance	Total
100	*540, 000	*1. 52	*1. 92	*3. 44
200	*960, 000	*1. 35	*1. 68	*3. 03
300	*1, 350, 000	*1. 27	*1. 56	*2. 93
300 (Houston)	†1, 600, 000			
400	*1, 776, 000	*1. 25	*1. 44	*2. 69

*From Snell, J. R. On the basis of a dumping fee only. Compost Science, 8(1): 17, Spring-Summer 1967.

†Personal communication from J. George, President, United Compost Services, Houston, Texas, to N. L. Drobny, Aug. 9, 1967.

GRUENDLER CRUSHER AND PULVERIZER COMPANY

Gruendler offers a composting system employing the windrow method of digestion. To date the only plant built is a 300-ton-per-day plant in Mobile, Alabama. This plant cost $1.6 million to build and began operation in 1966. Since that time, the plant has operated only intermittently for a variety of undetermined reasons. It was not possible during the course of this study to obtain estimated cost and performance data on any aspect of the operation either from the City of Mobile or from the Gruendler Company.

THE U.S. PUBLIC HEALTH SERVICE–TENNESSEE VALLEY AUTHORITY

In June 1967, PHS and TVA began operation of a 50-ton-per-day joint composting plant in Johnson City, Tennessee (Figure 55). This plant, financed by the Public Health Service, employs windrow digestion and represents the first attempt in the United States to obtain scientific data on this method of composting on a large scale.

Material is delivered to the plant and conveyed to a picking area where handsorters remove such items as rags, bottles, cardboard, magazines, and other noncompostables. These materials are not removed for salvage but rather to upgrade the quality of the compost. Tin cans are removed magnetically for the same purpose. The remaining waste material is ground in a Dorr-Oliver rasp, sewage sludge is added, and the material is then piled in windrows about 100 ft long, 9 ft wide, and 4 ft high. Total time in the windrow is about 35 days, during which period the compost is turned mechanically once or twice per week using a Cobey Windrow Turner.*

Problems have been reported with odors and with the control of fly populations. Another drawback of the windrow method, especially for urban centers, is the amount of land required. It has been estimated for example that 30 acres are required to serve a population of 100,000, compared to 5 acres for a typical mechanical digestion system.[31]

The Johnson City plant has not been in operation long enough to generate cost data for this system. Capital cost of the plant was $750,000,

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*Manufactured by General Products of Ohio, Crestline, Ohio.

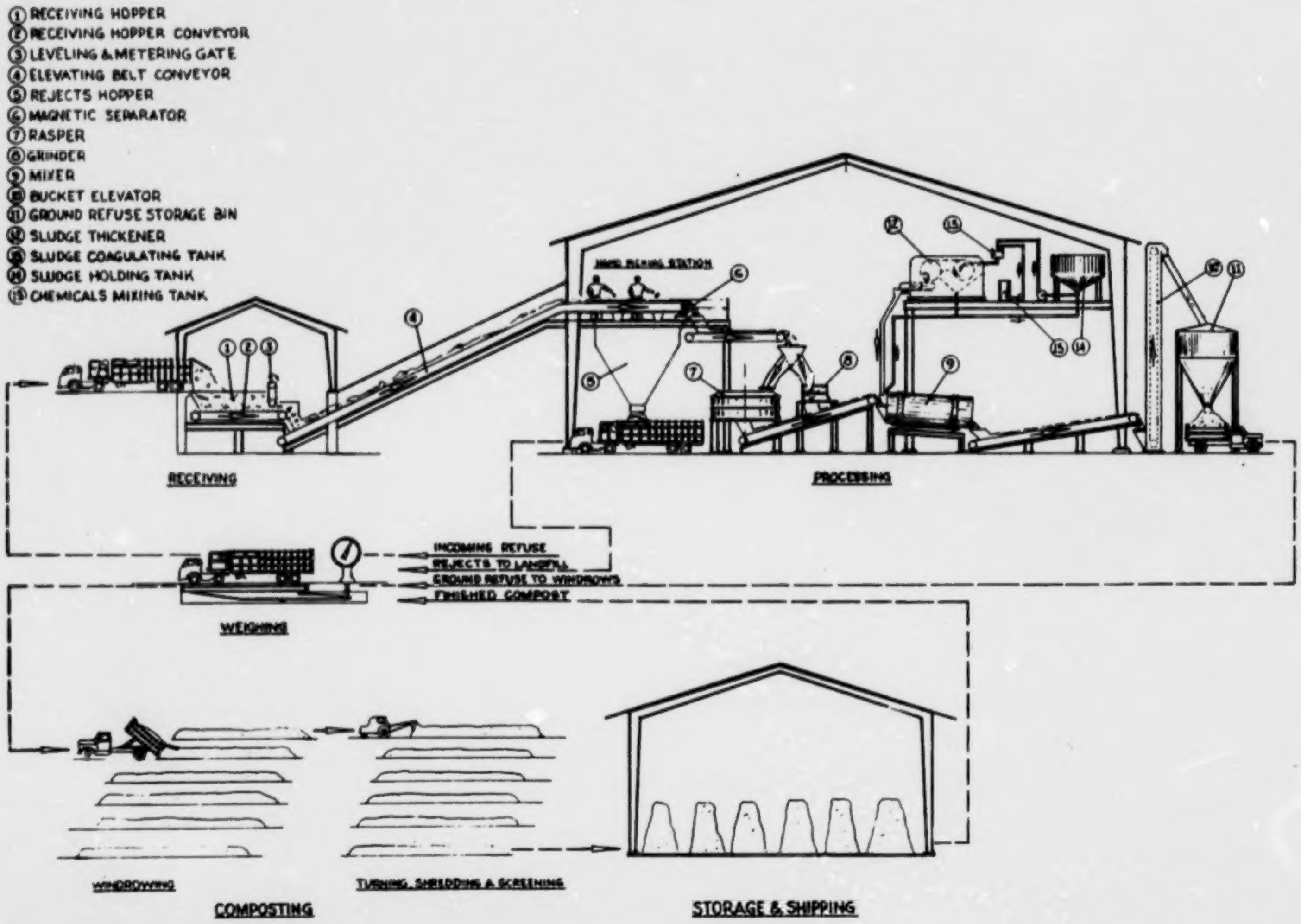
① RECEIVING HOPPER
② RECEIVING HOPPER CONVEYOR
③ LEVELING & METERING GATE
④ ELEVATING BELT CONVEYOR
⑤ REJECTS HOPPER
⑥ MAGNETIC SEPARATOR
⑦ RASPER
⑧ GRINDER
⑨ MIXER
⑩ BUCKET ELEVATOR
⑪ GROUND REFUSE STORAGE BIN
⑫ SLUDGE THICKENER
⑬ SLUDGE COAGULATING TANK
⑭ SLUDGE HOLDING TANK
⑮ CHEMICALS MIXING TANK
HAND PICKING STATION
RECEIVING
PROCESSING
INCOMING REFUSE
REJECTS TO LANDFILL
GROUND REFUSE TO WINDROWS
FINISHED COMPOST
WEIGHING
WINDROWING
TURNING, SHREDDING & SCREENING
COMPOSTING
STORAGE & SHIPPING

FIGURE 55. *Schematic flow diagram for USPHS–TVA Compost Plant, Johnson City, Tennessee. (From Wiley, John S.,* et al. *Concept and design of a 3-way composting project.* Compost Science, *7(2):11–14, Autumn 1966.)*

including experimental facilities which would normally not be included in a purely operational plant. As indicated in a previous section, the Johnson City plant affords an ideal opportunity to collect extensive and reliable data on the Dorr-Oliver rasp.

SUMMARY OF COMPOSTING COSTS AND OPERATIONAL REQUIREMENTS

Data in the preceding section summarize available information for composting operations in the United States. Because economic conditions differ significantly between countries, an attempt to correlate these data with that published for European compost plants[34] was unsuccessful, even upon adjustment of all European data to 1968 U.S. conditions.

Capital costs for both the IDC-Naturizer and the Fairfield-Hardy process are about 1.5 to 2 times that for the Metro and Snell system designs (Figure 56). Precise judgments cannot be made as to the exact reasons for these differences. The high cost of the IDC plants is probably related to the large digester building required. The high cost of the Fairfield-Hardy systems may be related to the pulping and dewatering equipment costs, the net cost of which would be expected to be greater than that for a hammermill for dry size reduction. These factors alone would not explain the total cost differences indicated above. In addition, it must be kept in mind that the data given were estimates for the most part and are based on limited operational experience. Estimates of total processing cost were available only for the Fairfield-Hardy and the John R. Snell systems (Figure 57). Extreme care must be exercised in the interpretation of these data since they are based upon estimates only. In addition, it has not been possible to determine the basis for the data for the Snell system in that detailed cost breakdown is not available. Detailed breakdowns for the Fairfield-Hardy system were available, and these data are considered to be much more reliable.

Data were obtained for the estimated labor and power requirements for various systems. Extremely close correlation was noted between the requirements for the Metro and Fairfield-Hardy systems. Requirements for the IDC-Naturizer system were significantly higher. Sufficient details on this system were not available to determine the reasons for the discrepancy (Figures 58 and 59).

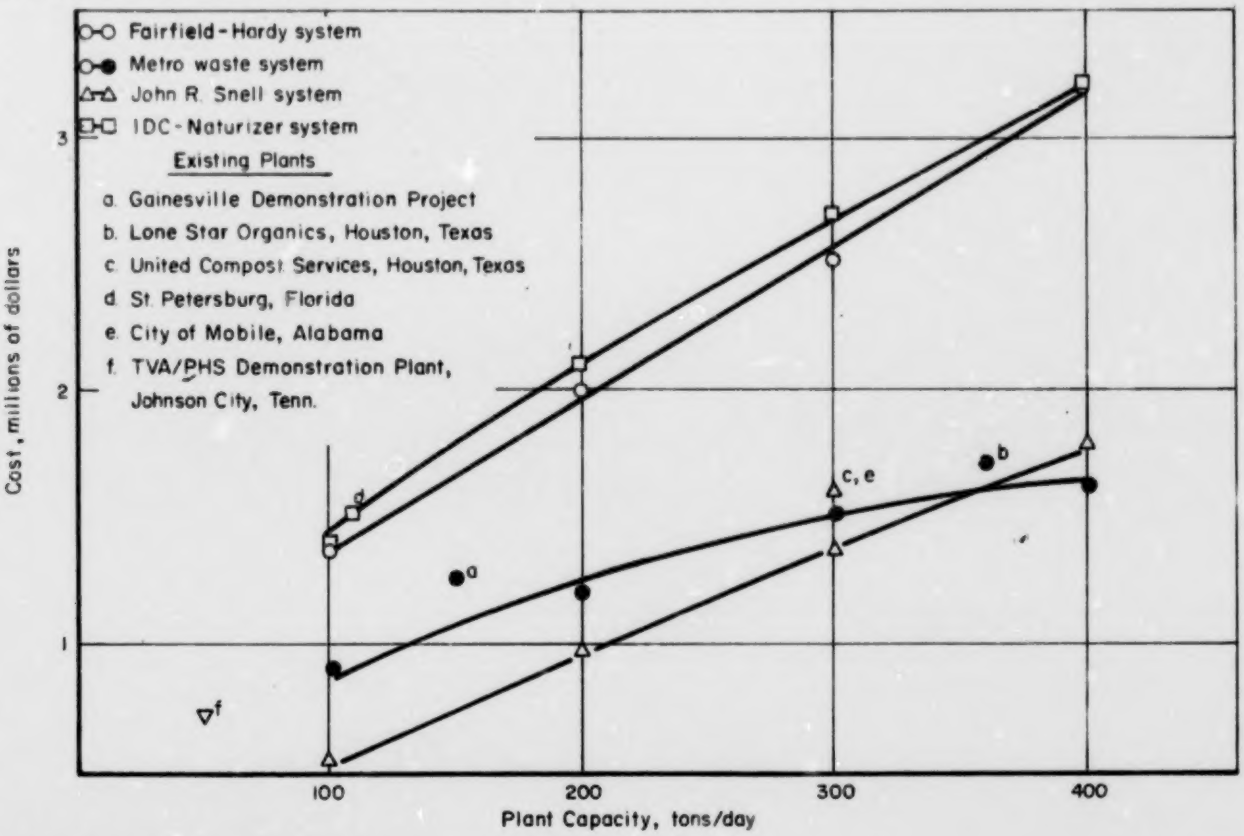

FIGURE 56. *Capital costs of composting systems.*

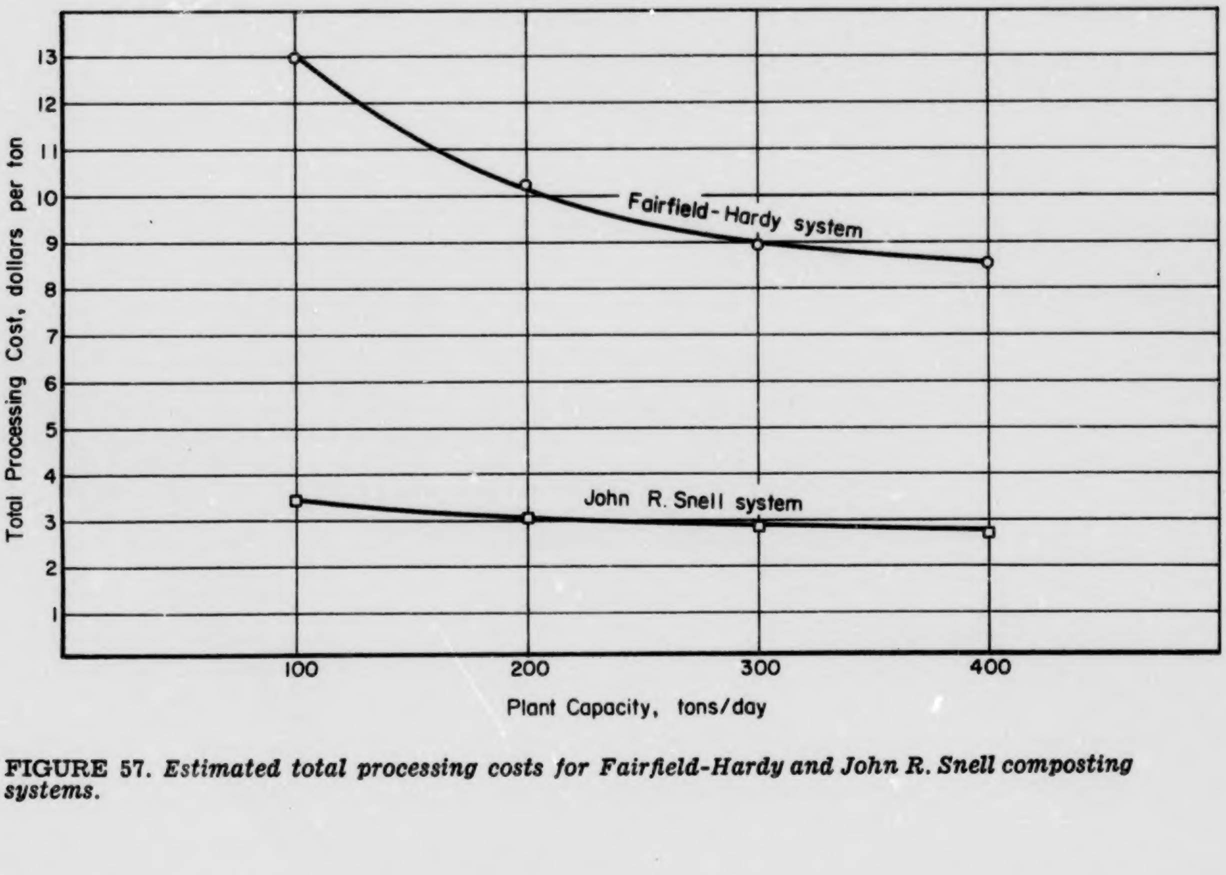

FIGURE 57. *Estimated total processing costs for Fairfield-Hardy and John R. Snell composting systems.*

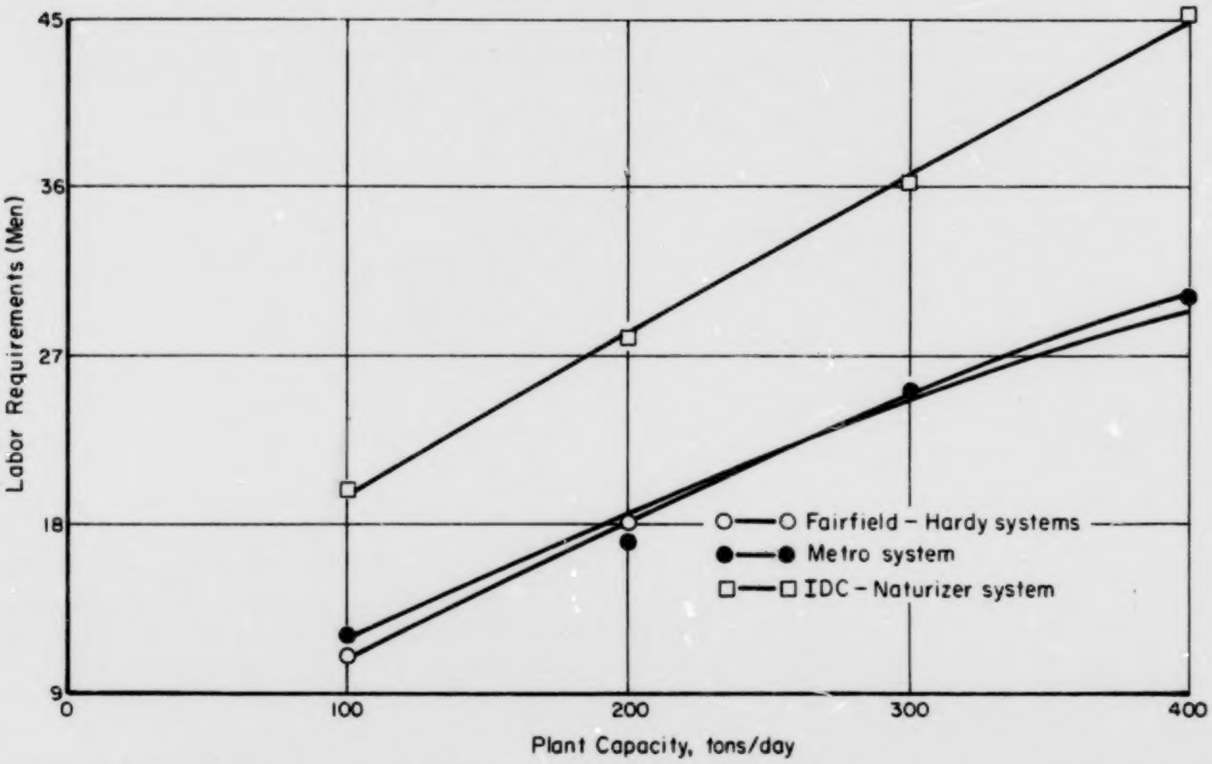

FIGURE 58. *Estimated labor requirements for composting systems.*

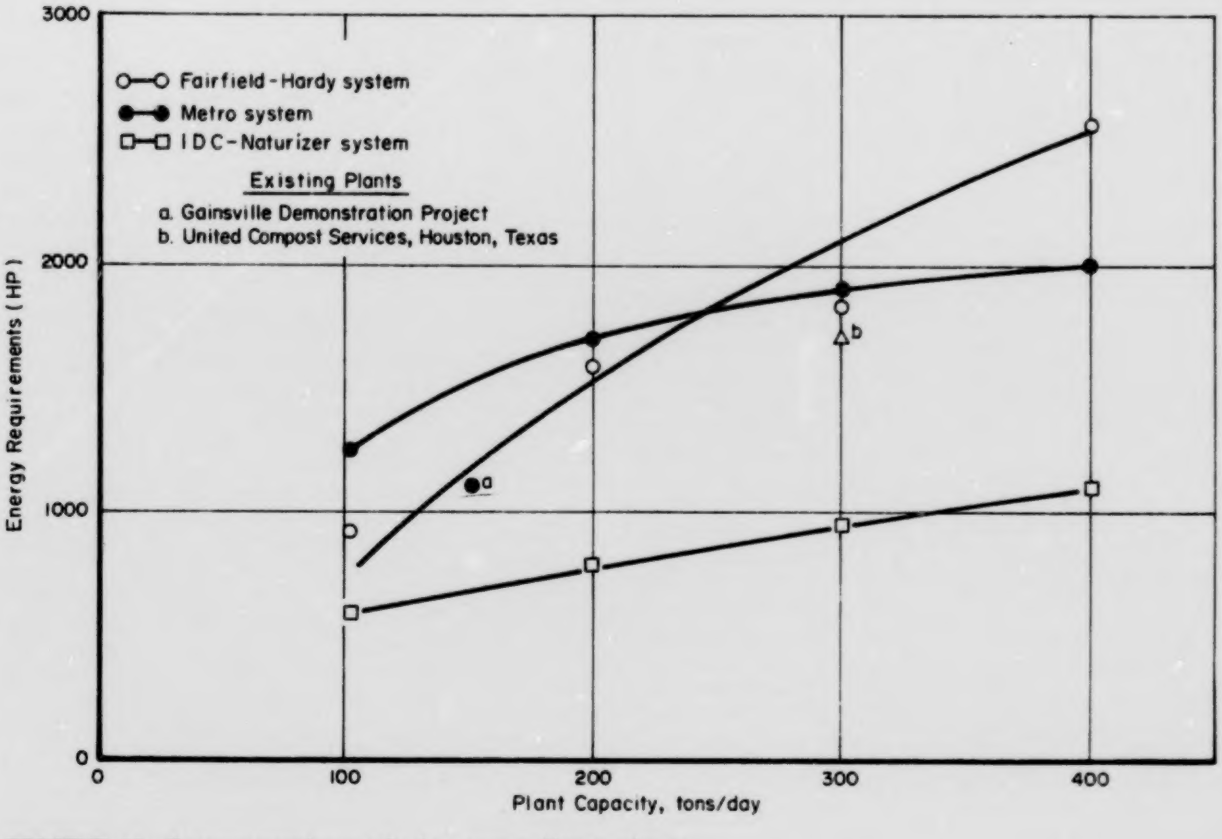

FIGURE 59. *Energy requirements for composting systems.*

HEAT RECOVERY

The recovery of waste heat in conjunction with incineration of municipal refuse has recently received special emphasis because of success in Europe, especially in Germany, with combined municipal incinerator steam power generating stations.

Waste-heat recovery systems for steam production may involve one of two general designs. The first employs a conventional refractory furnace followed by a waste-heat boiler. The second, and the one which is used widely in Germany and throughout Europe, employs a waterwall furnace. One advantage of a waterwall furnace is its increased heat transfer efficiency. This permits furnace temperature to be held within reasonable limits which would be exceeded in a refractory furnace without large quantities of excess air. Thus, the waterwall furnace will help alleviate air pollution control problems. Conventional refractory furnaces are normally designed for about 150 to 200 percent excess air, whereas there is some indication that waterwalled furnaces may operate satisfactorily on only 50 to 60 percent excess air. The smaller quantity of excess in waterwall systems results in smaller volumes of combustion products and, in turn, permits the use of smaller gas handling equipment. The disadvantages of a waterwall furnace are slightly higher capital and operating costs. Only one application of a waterwall furnace for waste-heat recovery exists in the United States.

Another general feature of waste-heat recovery systems for steam production is the need for auxiliary fuel to insure that constant steam production can be maintained despite moisture content and other variables that govern the heating value of refuse. European practice employs pulverized coal for this purpose whereas gas or oil would be more suitable for U.S. facilities.

Another form of waste-heat recovery, being studied by researchers in Connecticut and California, envisages power production through the use of gas fired turbines driven by effluent gases from municipal incinerators.[35,36]

REFUSE INCINERATION AND STEAM GENERATION IN EUROPE

The largest and most familiar European combined incineration/power generation facility is located in Munich, West Germany.[37] Two separate power generating facilities have been built: a 60-MW plant burning a combination of refuse and pulverized coal (with 40 percent of the power output supplied by refuse) and a 112-MW plant with 20 percent of the power output from refuse and 80 percent from pulverized coal. The reason for the "poorer" refuse to coal ratio for the larger plant is that the Munich refuse has a heating value of only 2,500 Btu per lb so that the bulk refuse throughput in terms of tons per day fed is the limiting factor on the larger design. A third plant identical to the second is now being constructed. With the three plants in operation, the city of Munich will be obtaining almost 70 MW of electricity from the combustion of 108 tons per hour of mixed municipal refuse.

These operations are technically and economically sound for Europe, but may not apply directly to conditions in the United States.[38] Fuel costs are relatively higher in Germany and the economic environment is more favorable for waste-heat utilization. In addition, the higher population density of West Germany (eight times that of the United States) has motivated strict air pollution control for a number of years. One technique for cooling effluent gases and hence controlling emissions is by heat transfer to produce steam. In addition, the Europeans have a greater concern for conservation and resource management. This also has contributed to the acceptance and success of waste-heat recovery in European refuse incinerators.

Finally, the difference in institutional arrangements must be considered. In Germany, power and utility services, as well as all waste collection and disposal services, are the responsibility of local governments. Consequently, the organizational and administrative aspects are considerably more simplified than they would be in the United States.

REFUSE INCINERATION AND STEAM GENERATION IN THE UNITED STATES

Waste-heat recovery from municipal solid waste incineration has been quite limited to date in the United States. In the past, it has been practiced to varying degrees in Boston, Massachusetts; Oyster Bay, New York; Providence, Rhode Island; and Hempstead, Long Island, New York (Merrick Plant). Waste-heat recovery is currently practiced in Atlanta, Georgia; Chicago, Illinois; Miami, Florida; Hempstead, Long Island, New York (Oceanside plant); and U.S. Naval Station, Norfolk, Virginia. All but the Norfolk plant employ conventional refractory furnaces followed by waste-heat boilers. The Norfolk plant is the first U.S. application of waterwall furnaces employing waste-heat recovery. Current U.S. applications are discussed below.

TABLE 27

SUMMARY OF OPERATING COSTS FOR CHICAGO SOUTHWEST MUNICIPAL INCINERATOR[41]

	Operating cost ($/ton)
Cost item:	
Labor (62 men)	$1. 92
Repairs	0. 73
Electrical	0. 19
Supplies	0. 60
Residue hauling	1. 05
Steam production (4,000 lb at $0.50/1,000 lb)	2. 00
	6. 49
Income item:	
Sales of steam (4,000 lb at $0.625/1,000 lb)	2. 70
Profit from salvage	0. 14
	2. 84
Net operating cost	3. 65
Amortization of capital cost	*1. 26
Total operation and maintenance cost	†4. 91

Source: Reference 41 plus Battelle estimates.

*These calculations assume 100 percent steam utilization. Reference 41 states that actual operating cost is $3.98 per ton implying that only 86 percent $\left(\frac{2.70-0.38}{2.70}\right)$ percent steam utilization is practiced.

†Reference 41 gives $5.24 per ton, again reflecting less than 100 percent steam utilization.

Atlanta, Georgia. The city of Atlanta operates two incinerators and several landfills. Tin cans are salvaged at both incinerators. At the Mayson incinerator, which has a design capacity of 700 tons per day, waste-heat recovery and steam generation are practiced.[39,40]

Four 175-ton-per-day combined grate and rotary kiln furnaces are installed at the Mayson plant. Two were installed in 1942 at a cost of $800,000, and two in 1952 at a cost of $1,250,000. Total cost in 1968 dollars has been calculated to be $4,567,000. Steam produced at the Mayson plant is 175 psig saturated and is sold at $0.20 per 1,000 lb to the Georgia Power Company to heat buildings in downtown Atlanta.

Chicago, Illinois. The city of Chicago generates steam at its Southwest Incinerator.[39,41] The Southwest plant has four 300-ton-per-day combined grate and rotary kiln furnaces. Metal salvage in addition to waste-heat generation is practiced at the Southwest plant. The incinerator was constructed in 1963 at a cost of $6,825,000. Of the total cost, $1,625,000 was for the steam plant and distribution system.[41]

Steam generated at the Southwest plant is produced for about $0.50 per 1,000 lb and is sold to a private contractor for $0.625 per 1,000 lb. It is used mostly in the stockyard area of Chicago. Since demand is low in the summer, the full steam capacity is not utilized during this period.

The Southwest incinerator is operated 24 hr per day, 7 days per week (Table 27). Waste heat is supplied to four boilers, each capable of generating 50,000 lb of steam per hr. Based on 1,200 tons per day of refuse, this amounts to a design capacity of 2.0 lb of steam per lb of refuse incinerated.

Miami, Florida. Steam is recovered from a 900-ton-per-day municipal incinerator in Miami, Florida.[42] The incinerator, constructed in 1954, cost $3 million. Steam produced at 250 psig and 406 F is sold to the Jackson Memorial Hospital for $0.70 per 1,000 lb. Approximately three lb of refuse are required to produce one lb of steam. This appears to be somewhat less efficient than the other installations discussed in this section.

Hempstead, Long Island, New York. A 750-ton-per-day municipal owned incinerator employing waste-heat recovery both for steam generation and water desalination was recently put into operation at Hempstead's Oceanside plant at a total cost of $6 million.[43-46] Steam is produced in two boilers, each having a capacity of 85,000 lb of steam per hr (462 F and 460 psig), and is used to produce 2,500 KW power to operate the plant. Exhaust steam from the power plant is used to produce about 500,000 gal per day of fresh water for cooling, boiler makeup water, and fly-ash scrubbing within the plant.

TABLE 28

SPECIFICATIONS FOR BOILER-FURNACE UNITS AT U.S. NAVAL STATION, NORFOLK, VIRGINIA*

Mixed refuse (tons per day)	180
Heating value as fired (Btu/lb)	5,000
Moisture (percent)	25
Noncombustible (percent)	12.5
Steam production	
With refuse at 5,000 Btu/lb (lb/hr)	50,000
With drier refuse or with refuse plus oil (lb/hr)	60,000
With oil only (lb/hr)	50,000
Design stoker loading	
lb refuse/sq ft/hr of effective grate surface	65
Heat release	
Btu/hr/sq ft effective grate surface	325,000
Btu/cu ft primary furnace volume (max)	25,000
Minimum gas temperature leaving primary furnace at 50 percent of rated load (degree F)	1,400
Steam pressure (psig)	275
Steam quality	Saturated
Feedwater temperature (degree F)	288
Exit gas temperature from boiler at design refuse capacity (degree F)	580

*From Moore, H. C. Refuse fired steam generator at navy base, Norfolk, Va. *In* Incineration of Solid Wastes; proceedings, MECAR Symposium, New York Mar. 21, 1967. p. 10-21.

The plant design employs two 300-ton-per-day refractory furnaces which burn mixed solid waste, and one 150-ton-per-day unit for bulk rubbish. The gases from the two large furnaces discharge through boilers for heat recovery. Heat is not recovered from the bulk rubbish unit. Based upon steam production of 170,000 lb per hr and solid waste throughput of 600 tons per day, approximately 3.4 lb of steam are produced per lb of refuse.

U.S. Naval Station, Norfolk, Virginia. Recently the U.S. Naval Station at Norfolk, Virginia, put into operation the nation's first waterwall solid waste incinerator.[47-49] Capital cost of the system was $2.2 million.

Feed to the system includes large quantities of crates and packing materials, in addition to the normal rubbish. The system is designed for refuse having a heating value of 5,000 Btu per lb and a moisture content of 25 percent (Table 28). Two 180-ton-per-day furnaces are used, each capable of generating 50,000 lb of 275 psig dry saturated steam per hr. This corresponds to about 3.33 lb of steam per lb of waste. An auxiliary oil burner is also capable of supplying 50,000 lb of 275 psig dry saturated steam per hr. The steam produced saves over 5 million gal of fuel oil per year.

Houston, Texas. A facility is planned for Houston, Texas, which will incinerate 10,000 tons per month (about 330 tons per day) of industrial solid waste and produce 100,000 lb of steam per hr.[50] This corresponds to a steam production rate of 3.57 lb of steam per lb of waste. Steam will be sold for industrial consumption. The plant is a joint venture of several local industries utilizing one disposal agency, Consolidated Oxidation Process Enterprises. The plant will be designed by Foster Wheeler Corp. and Nichols Engineering Research Corp., and will employ a waterwall furnace. The plant is expected to cost $5 million and is scheduled for completion in 1969.

OPERATING CHARACTERISTICS AND COSTS OF SELECTED INCINERATOR SYSTEMS

Large scale systems for heat recovery and solid waste incineration have not been in operation long enough to generate operating data. Certain relationships which governed recent designs have been published. It must be emphasized, however, that this information has not been confirmed on an operational scale.

A recent paper describing the Norfolk plant reported anticipated steam production as a function of the heating value of the refuse, refuse throughput, and percent excess air (Figures 60 to 62).[49] The curves are based upon the design specifications for the Norfolk plant (Table 28).

Similar but less complete data have recently been presented in a paper summarizing European experience with emphasis on potential applications of waste heat recovery in the United States.[51] Assuming 88 percent excess air, the refuse heating value was used to compute steam production. These values can be compared to those of the Norfolk plant using 50 percent excess air (Figure 63). As expected, a slightly higher specific

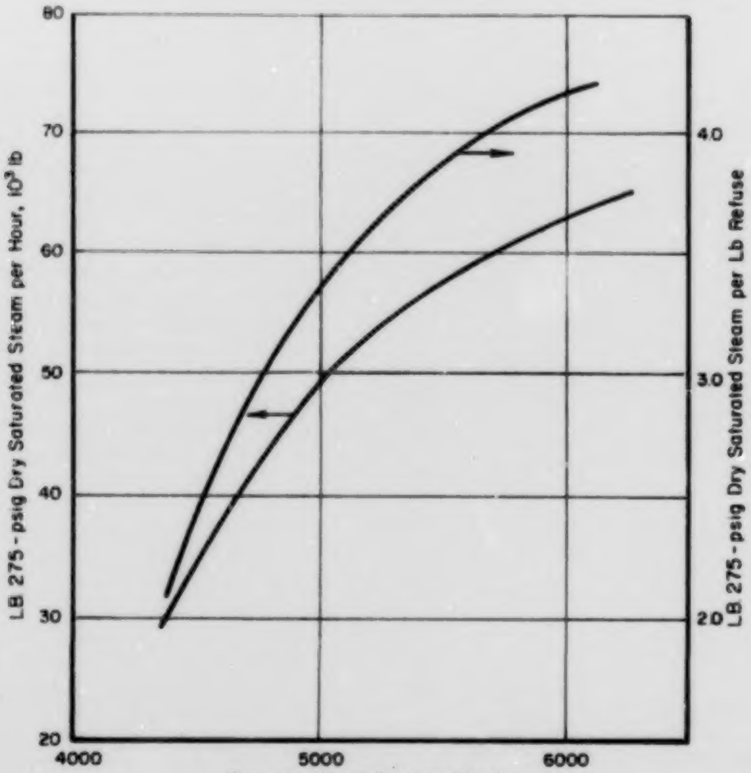

FIGURE 60. *Estimated steam production at Norfolk from refuse having various heat capacities. Assume 180 tons/day and 50 percent excess air. (Based upon: Moore, H. C. Refuse fired steam generator at navy base, Norfolk, Va.* In *Incineration of Solid Wastes; Proceedings, MECAR Symposium, New York, Mar. 21, 1967. p. 10–21.)*

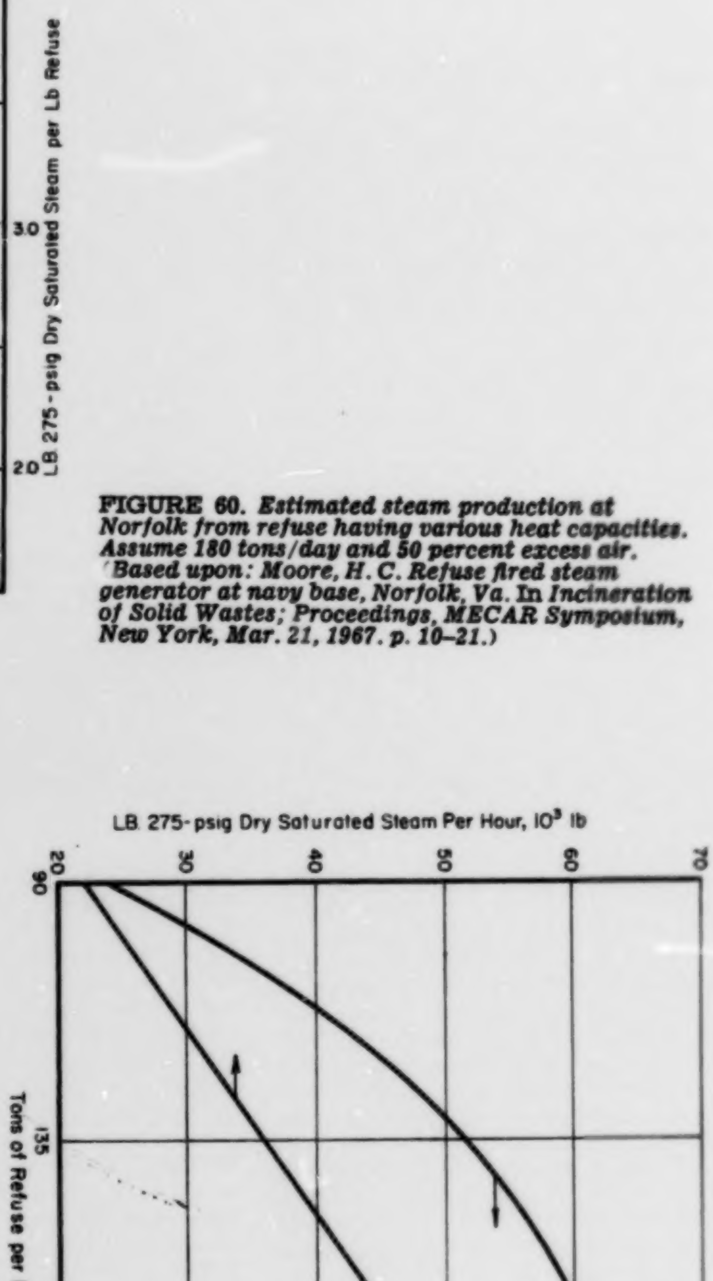

FIGURE 61. *Estimated steam production at Norfolk from refuse at various loads. Refuse of 5,000 Btu/lb and 50 percent excess air is assumed. (Based upon: Moore, H. C. Refuse fired steam generator at navy base, Norfolk, Va.* In *Incineration of Solid Wastes; Proceedings MECAR Symposium, New York, Mar. 21, 1967. p. 10–21.)*

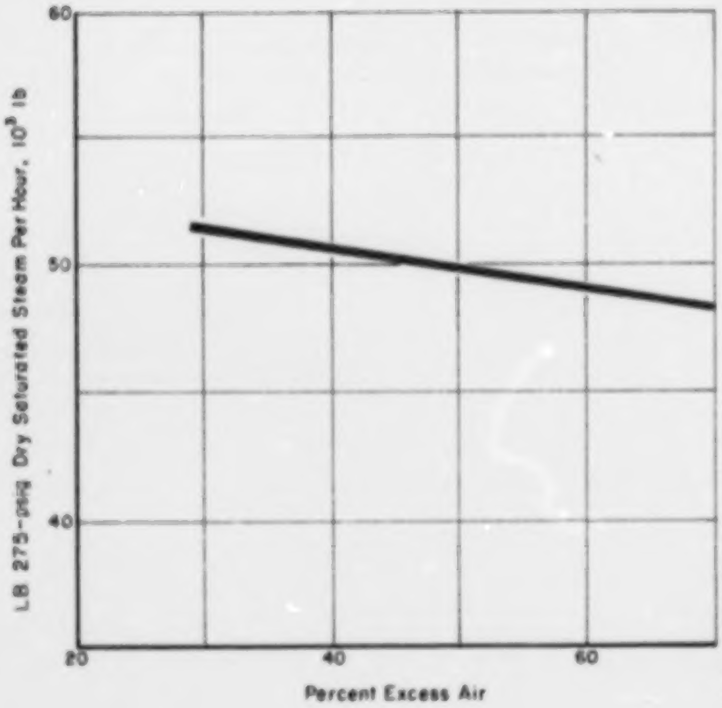

FIGURE 62. *Estimated steam production at Norfolk from refuse as a function of excess air. Assume 180 tons/day—5,000 Btu/lb. (From Moore, H. C. Refuse fired steam generator at navy base, Norfolk, Va. In Incineration of Solid Wastes; Proceedings, MECAR Symposium, New York, Mar. 21, 1967. p. 10–21.)*

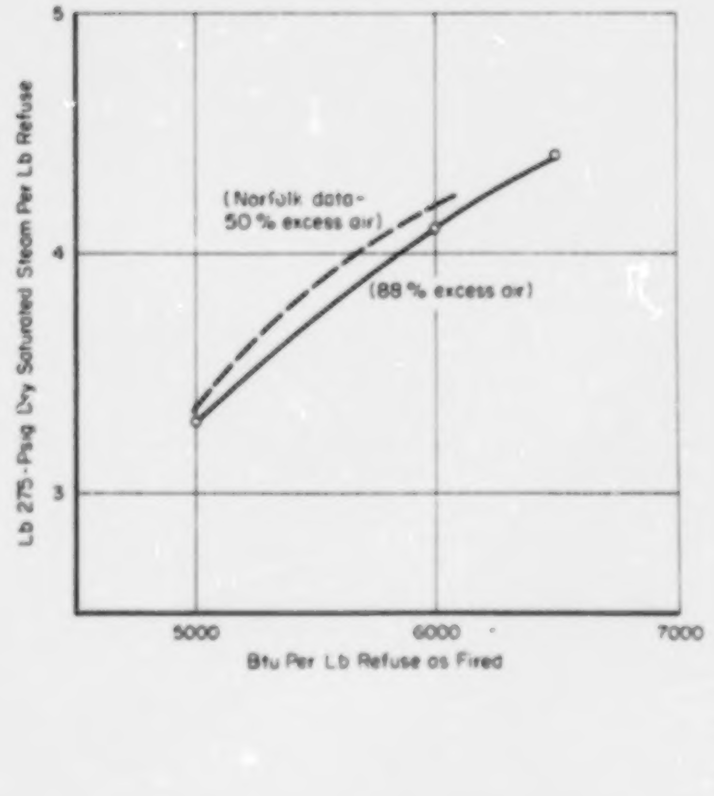

FIGURE 63. *Estimated steam production from refuse having various heat capacities. Assume 88 percent excess air. (Based upon: Stabenow, G. Performance and design data for large European refuse incinerators with heat recovery. In Proceedings; 1968 National Incinerator Conference, New York, May 5–8, 1968. New York, American Society of Mechanical Engineers. p. 278–286.)*

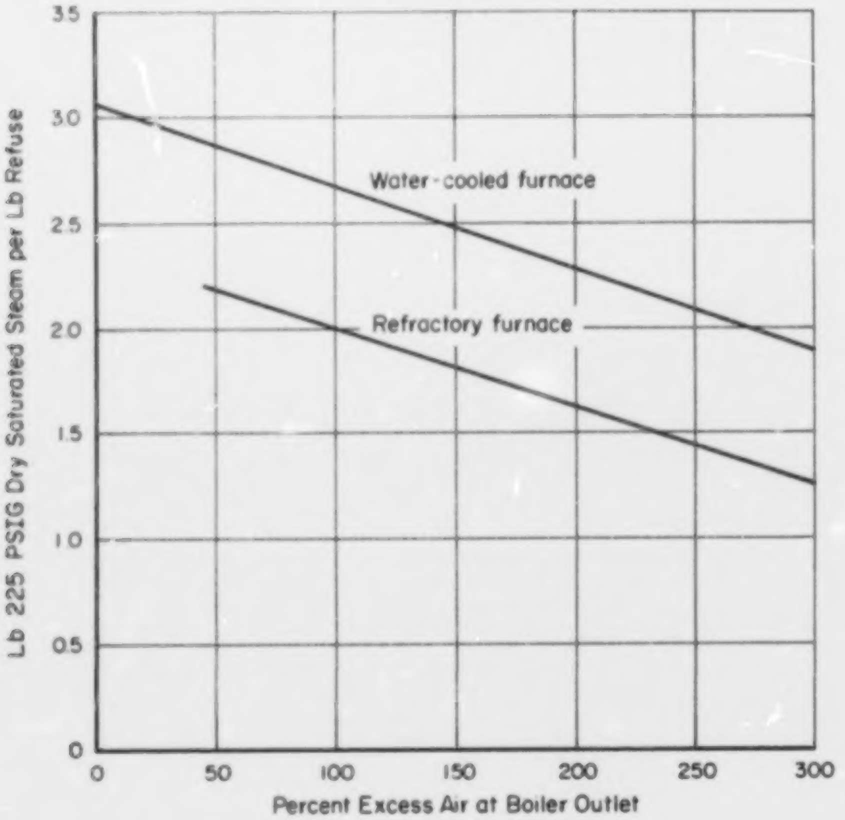

FIGURE 64. ***Estimated effect of excess air on steam generating capacity of 800-ton-per-day refuse incinerator. Assume 20 percent moisture in refuse. (From Day & Zimmermann, Engineers & Architects. Heat recovery.*** **In *Special studies for incinerators; for the Government of the District of Columbia, Department of Sanitary Engineering. Public Health Service Publication No. 1748. Washington, U.S. Government Printing Office, 1968. p. 55–73.)***

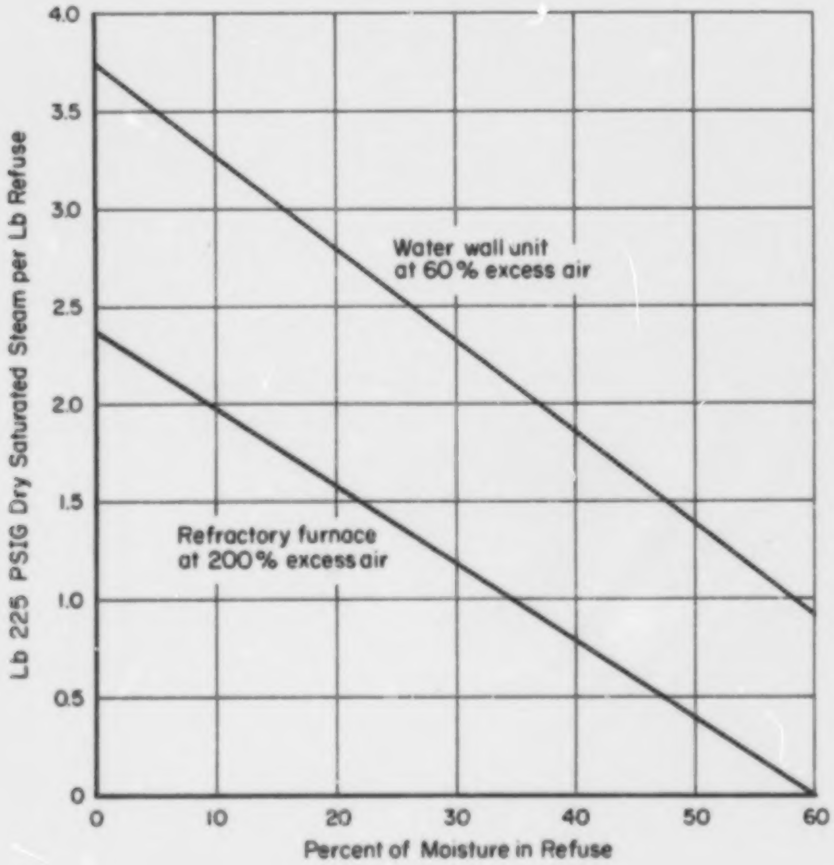

FIGURE 65. ***Estimated effect of refuse moisture content on steam generating capacity of 800 ton per day refuse generator. (From Day & Zimmermann, Associates. Heat recovery.*** **In *Special studies for incinerators; for the Government of the District of Columbia, Department of Sanitary Engineering. Public Health Service Publication No. 1748. Washington, U.S. Government Printing Office, 1968. p. 55–73.)***

steam production rate results for the lower percentage of excess air.

In addition, Day & Zimmermann Associates, Philadelphia, have prepared estimates on waste-heat recovery for an 800-ton-per-day incinerator for the District of Columbia.[52] These studies evaluated the following: conventional refractory furnace with spray cooling of flue gas; conventional refractory furnace with spray cooling of flue gas and boiler in by-pass flue; waterwall furnace with convection boiler; and waterwall furnace with spray cooling of flue gas. Estimates of steam-generating capacity as a function of excess air and as a function of refuse moisture content were presented (Figures 64 and 65).

All of the data in this section represent engineering estimates and are not the results of direct operational experience. The potential pitfalls in the use of such data must be emphasized.

Capital costs of incinerators with or without heat recovery. The following section summarizes actual and estimated costs of incinerators with and without waste-heat recovery. The previously presented cost data on U.S. waste-heat recovery has been adjusted to 1968 conditions using the *Engineering News Record* Building Cost Index (Table 29).

In their report to the District of Columbia, Day & Zimmermann provided partial capital cost estimates for the systems investigated.[52] The costs covered only those items expected to vary from one design to another. The constant cost items listed below were not included in the estimates: dumping floor, plant enclosure, cranes with crane bay steel and enclosure, offices, locker rooms, stair towers, elevators, storage room, machine shop, heating and ventilating, plumbing and sanitary waste, electricity for above items, site development, roads, paving, land, scale house, and scales. The total cost of the above items, excluding land and site developments, were estimated by Battelle to ranges between $100,000 and $200,000, averaging $150,000. The capital cost estimates for the systems studied by Day & Zimmermann were summarized (Table 30) and may be compared with published data on conventional refractory furnaces without heat recovery (Tables 31 and 32).[53, 54] The Day & Zimmermann cost estimates may be used to generate cost functions based on a conventional engineering estimating factor which states that cost is proportional to the six-tenths power of capacity (Figure 66). Data presented earlier show that

TABLE 29

CAPITAL COSTS OF U.S. INCINERATION EMPLOYING WASTE-HEAT RECOVERY

Installation	Year built	Capacity (tons/day)	Capital cost	
			(Actual)	(1968)*
Atlanta, Georgia	1942 and 1952	700	$2, 050, 000	$4, 567, 000
Chicago, Illinois	1963	1, 200	6, 825, 000	8, 300, 000
Miami, Florida	1954	900	3, 000, 000	4, 880, 000
Hempstead, L.I., New York (Oceanside plant).	1964	750	6, 000, 000	6, 500, 000
U.S. Naval Station, Norfolk, Virginia.	1966	360	2, 200, 000	2, 540, 000

*Calculated using "Engineering News Record" Building Cost Index.

TABLE 30

ESTIMATED CAPITAL COSTS FOR 800-TON-PER-DAY MUNICIPAL INCINERATOR EMPLOYING WASTE-HEAT RECOVERY

System description	Variable capital cost*	Constant capital cost†	Total capital cost
Conventional refractory furnace with spray cooling of flue gas	$3, 583, 000	$150, 000	$3, 733, 000
Conventional refractory furnace with spray cooling boiler in by-pass flue	5, 737, 000	150, 000	5, 887, 000
Waterwall furnace with convection boiler	4, 297, 000	150, 000	4, 447, 000
Waterwall furnace with spray cooling of flue gas	4, 303, 000	150, 000	4, 453, 000

*Based upon: Day & Zimmermann, Associates. Heat recovery. *In* Special studies for incinerators; for the Government of the District of Columbia, Department of Sanitary Engineering. Public Health Service Publication No. 1748. Washington, U.S. Government Printing Office, 1968. p. 55–73.

†Battelle estimate.

TABLE 31

CAPITAL COSTS OF CONVENTIONAL REFRACTORY MUNICIPAL INCINERATORS*

Installation	Capacity (tons/day)	Capital cost	
		ENR building cost index=580	1968 ENR building cost index=700
Alexandria, Virginia	200	$922, 000	$1, 100, 000
Lexington, Kentucky	200	750, 000	900, 000
Evanston, Illinois	180	881, 000	1, 060, 000
Wauwatosa, Wisconsin	165	835, 000	1, 000, 000
Portsmouth, Virginia	300	1, 068, 000	1, 170, 000

*From Clarke, S. M. Incinerating plant costs. *Public Works*, 93(9): 122–23, Sept. 1962.

TABLE 32

CAPITAL COSTS OF CONVENTIONAL REFRACTORY FURNACE MUNICIPAL INCINERATORS*

Installation	Year constructed	Capacity (tons/day)	Capital cost	
			(Actual)	(1968)
Buffalo, New York	1953	400	$1, 500, 000	$2, 400, 000
Baltimore, Maryland	1955	800	2, 153, 000	3, 350, 000
Cincinnati, Ohio	1954	500	1, 494, 000	2, 330, 000
Hartford, Connecticut	1954	600	1, 434, 000	2, 240, 000
Rochester, New York	1956	600	2, 110, 000	3, 100, 000

*Source: Michaels, A. Incineration. *In* Public Works Engineers Handbook, Chicago, American Public Works Association, 1957.

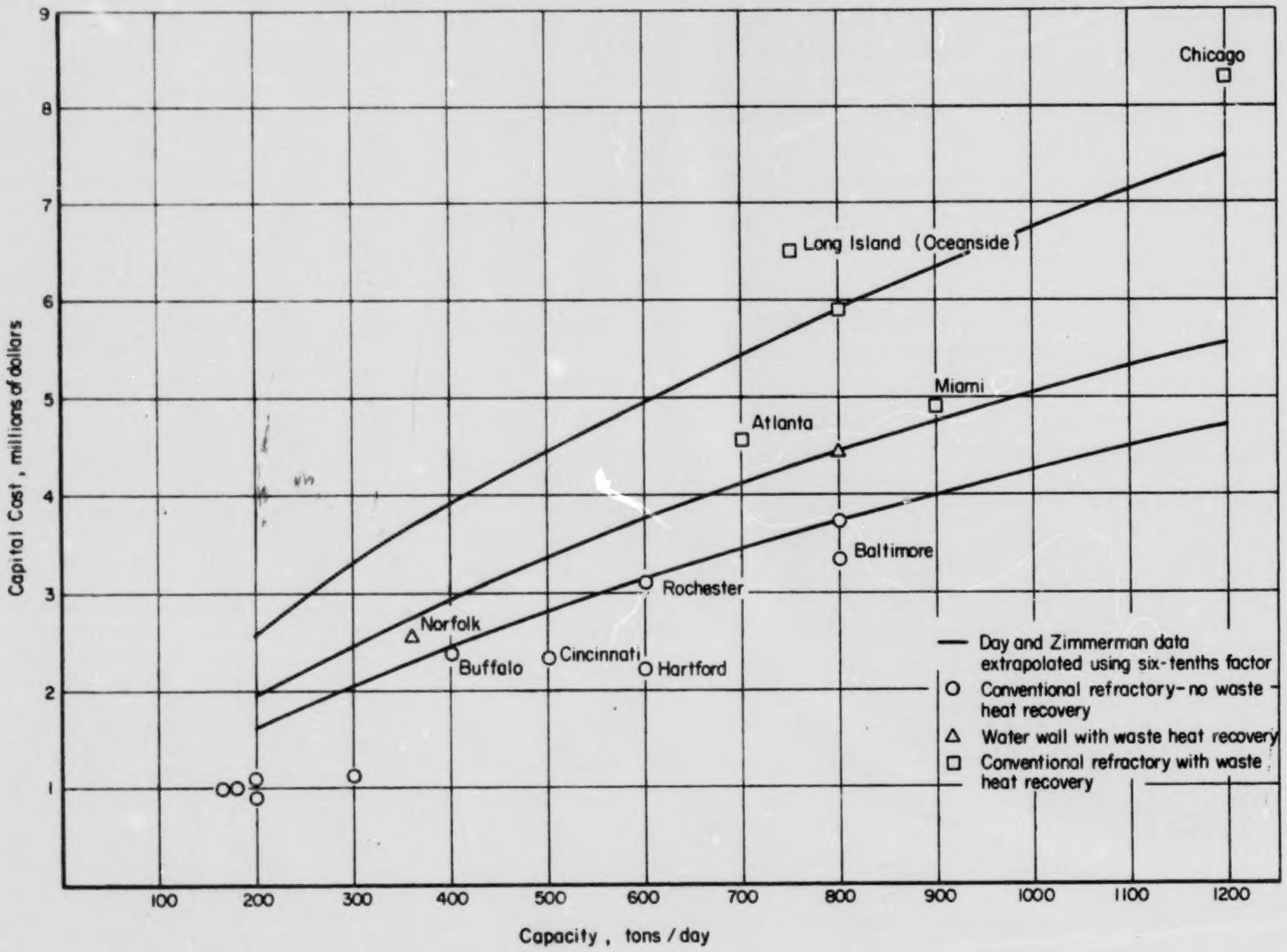

FIGURE 66. *Capital costs of municipal incinerators.*

reasonable correlation exists for the waterwall designs. The Day & Zimmermann extrapolated cost data for the conventional refractory without heat recovery indicate a trend somewhat higher than the adjusted costs for existing installations. This may be attributed to the more costly air pollution control equipment required on today's incinerators.

Economics of Waste-Heat Recovery. Data on cost of steam production in conjunction with municipal solid waste incineration in the United States are very limited. It has been noted that the additional cost to produce steam at the 1,200-ton-per-day Chicago Southwest Refractory Furnace Incinerator was about $0.50 per 1,000 lb. Estimates on the additional cost of steam production in the Day & Zimmermann systems were $1.06 and $0.49 per 1,000 lb for 800-ton-per-day refractory and waterwall systems, respectively.

To evaluate the implication of these costs assumes a conservative production of 2 lb of steam per lb of refuse and an additional cost of $0.50 per 1,000 lb to produce steam. Since this cost is additional to that of waste incineration, to break even, the steam produced must be sold for at least $0.50 per 1,000 lb. To justify waste-heat recovery, it must be sold at a profit unless there are economic justifications for its production. If steam can be sold for $0.60 per 1,000 lb, this results in recovery of $0.10 per 1,000 lb of the costs of incineration. Production of 2 lb of steam per lb of refuse corresponds to 4,000 lb of steam per ton of refuse, or an incineration cost recovery of $0.40 per ton of refuse. The Chicago costs, where steam sold at $0.625 per 1,000 lb, resulted in a net income of $0.50 per ton of refuse (Table 27).

On the basis of existing data, it appears that only about 10 percent of incineration cost could be saved by employing waste heat recovery, if there is a customer willing to buy the steam. This is not always the case. For instance, Day & Zimmermann concluded that waste-heat recovery could not be justified. This was due to

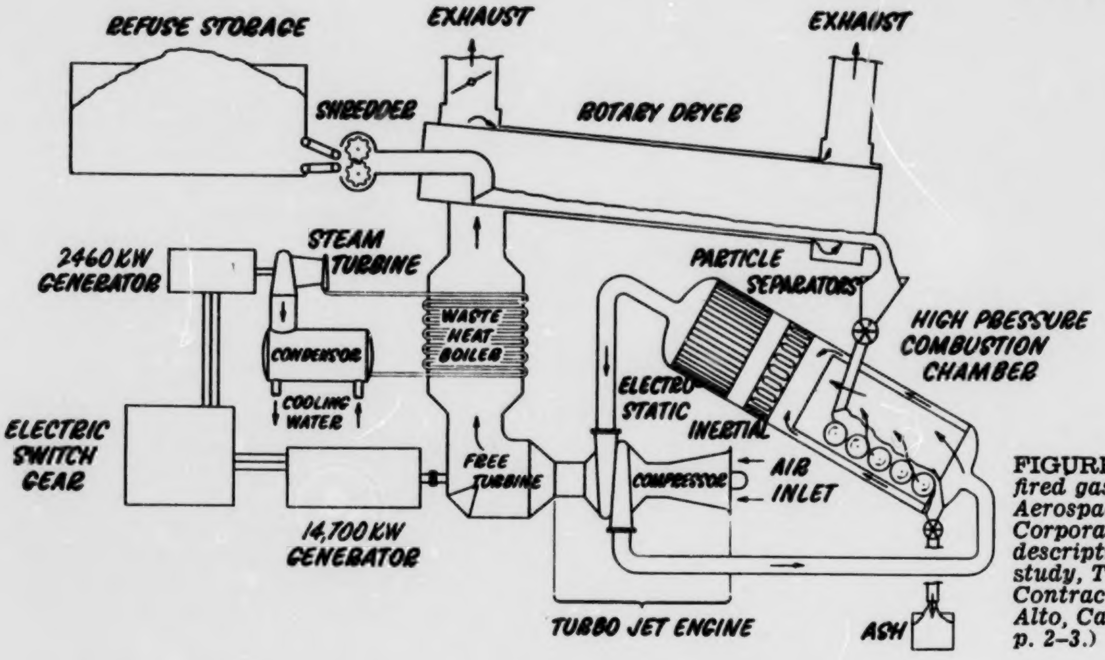

FIGURE 67. *CPU-400 Refuse-fired gas turbine. (From Aerospace Commercial Corporation. CPU-400 Technical description and economics study, TR 6702; report on Contract PH 86-67-259. Palo Alto, California, Sept. 1967. p. 2-3.)*

the lack of a customer within the vicinity of the incinerator who could justify a demand for an interruptable supply of steam.

Control of air pollution is an additional factor that cannot be evaluated on the basis of existing data. More stringent controls may lower the additional cost of steam production through assignment of a portion of the equipment and operating costs to pollution control rather than to steam production. For example, assuming (1) additional heat-recovery equipment cost to equal air pollution control equipment costs and (2) steam to be sold at $0.60 per 1,000 lb, the net profit per ton of refuse would be $2.40 per ton or less than half the cost of incineration. Thus, cost allocation techniques are significant in evaluating waste-heat recovery economy. Sufficient data are not available to determine the true net cost of waste-heat recovery.

REFUSE-FIRED GAS TURBINES

Two research investigations are studying the possibility of using refuse-fired gas turbines for power production. One system, the CPU-400, is being investigated by Aerospace Commercial Corporation (Figure 67).[35] A Pratt & Whitney FT4A-8 stationary jet engine gas turbine or a General Electric Series 5000 industrial gas turbine-generator supplies high-pressure air for the refuse combustion and to electric power generation. It is claimed that the CPU-400 burns refuse at 7 to 12 times atmospheric pressure. Three alternative combustion systems have been identified; direct combustion, fluidized bed, and pyrolysis (Figure 68).

Based upon selected assumptions and theoretical calculations, the system should generate power at a cost of 1.7 mills per kwh. However, the technical validity of the basic assumptions remains to be established. Potential problem areas may be:

(1) Electrostatic collectors are required to operate at 1,500 F. (Battelle is aware of two attempts to develop such a system, neither of which was successful.)

(2) No provision is made to guard against air bleeds from the compressor, although leakage of a few percent of the air would eliminate all power capability.

(3) Considerable expense (perhaps several million dollars) would be required to adapt the Pratt & Whitney unit by providing remote ducting for an outside combustor. (The General Electric turbine, however, has already been altered.)

(4) The estimates for additional maintenance due to fly-ash erosion assume no more than that normally expected from burning No. 6 fuel oil. (However, in high velocity turbines any ash content would create extensive erosion. It is not likely that zero ash content could be attained with existing technology.)

These comments are not intended as criticism of the research, since most research programs are aimed at overcoming technical obstacles. The comments should put the apparently attractive power costs in the proper perspective.

Studies at the University of Hartford have explored a system similar in concept to the CPU-400 unit.[36] The system involves both the production of electric power in a high-temperature and pressure combustion process and the manufacture of a ceramic-metal composite. The system consists of three main components: a Pratt & Whitney FT-4 gas turbine, a large hammermill, and the materials processing system. As in the CPU-400, significant erosion problems would be expected from the extremely high velocities characteristic of aircraft turbines. This and other substantial problems appear to be unduly discounted in the preliminary feasibility study. Estimated net power-generating costs were in the range of 0.4 to 3.3 mills per kwh, depending upon the income from recovering metal scrap

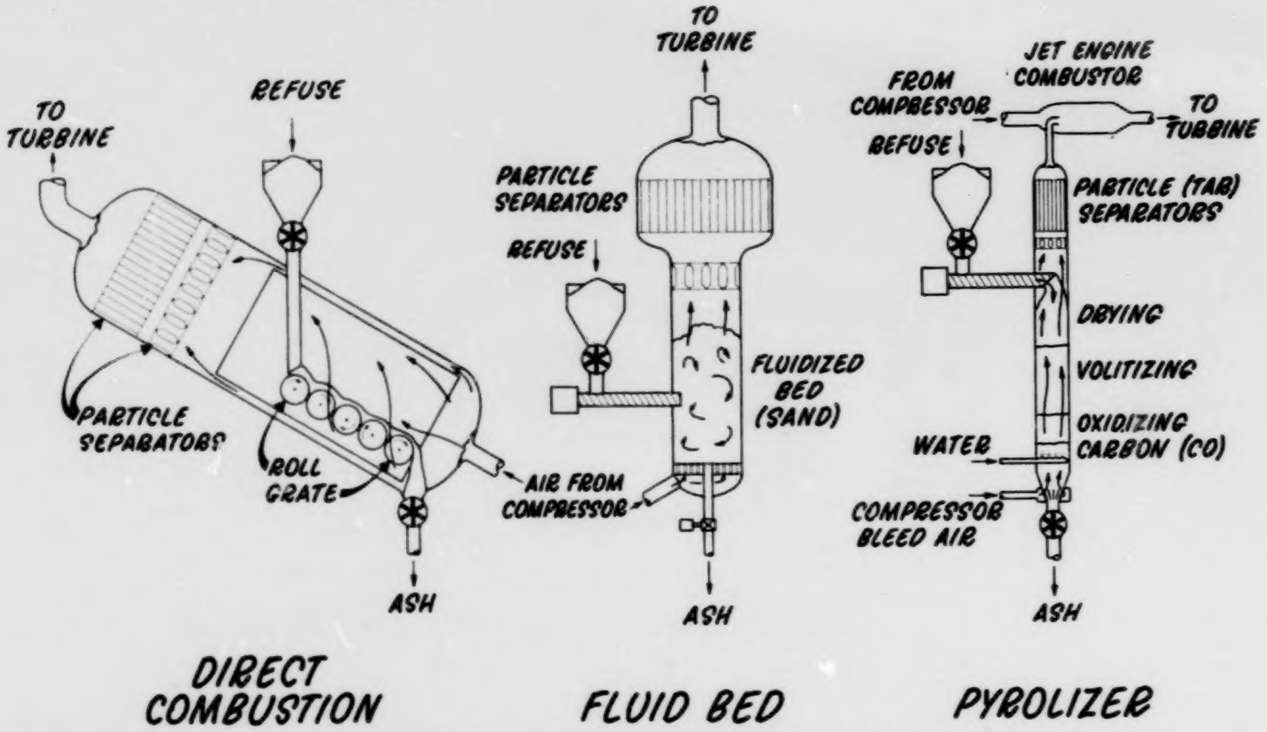

FIGURE 68. *Alternative combustor types.* (*From Aerospace Commercial Corporation. CPU–400 Technical description and economics study, TR 6702; report on Contract PH 86–67–259. Palo Alto, California, Sept. 1967. p. 2–16.*)

and manufacturing the ceramic material. In addition, significant problems could arise in developing sufficiently strong bonds between silicates and the metal scrap. Problems would be similar to those in enameling operations where process variables must be closely controlled.

The above investigations discount previous unsuccessful attempts to use solid fuel containing ash to generate power in gas turbines. To date, the high degree of ash removal needed to protect the turbine blades from erosion is not possible. Mr. P. G. LaHaye, the General Electric Company, in discussing the closed-cycle coal-fired turbine stated:

"Over the past two decades, several investigations have been undertaken in the United States and abroad, directed at developing a practical commercial coal-fired gas turbine. The best known programs originated in the United States and Canada were the exhaust-fired cycle program of Professor D. L. Mordell and associates at McGill University, Toronto, Canada; the direct-fired locomotive gas turbine development program by the Locomotive Development Committee of the Bituminous Coal Institute at Dunkirk, New York; and the coal gasification studies jointly undertaken by the Babcock & Wilcox Company and the General Electric Company.

To date, none of these programs have sufficiently reduced first costs of capital equipment or improved cycle performance to warrant their commercial exploitation."[58]

The potential of the refuse-fired gas turbines cannot be evaluated meaningfully without regard to the experiences mentioned above. Since the major obstacle is blade erosion, cleaning of the gases should be attacked first.

CHEMICAL CONVERSION

A great many processes for converting solid waste into usable products can be grouped loosely under the term "chemical conversion." In this report, chemical recovery includes thermal, chemical, and biological processes for the treatment of mixed municipal solid waste. Chemical processes directed toward recovery of a specific fraction of solid waste such as tin can reutilization, secondary-fibers production, glass reforming, etc., are covered in later sections. Specific processes presented here are pyrolysis, the application of heat in the absence of oxygen; hydrolysis, the conversion of cellulosic materials to sugars by acids or bases; and biochemical processes, which include the manufacture of yeast or alcohols.

PYROLYSIS

Pyrolysis, often termed "destructive distillation," is a process in which organic material is heated to a high temperature (1,000 F to 2,000 F) in either an oxygen-free or low-oxygen atmosphere. Unlike combustion in an excess of air, which is highly exothermic and primarily produces heat and carbon dioxide, pyrolysis of organic material is analogous to a distillation process and is endothermic. The high temperatures and lack of oxygen in the pyrolysis of solid waste result in a chemical breakdown of the organic materials into three component streams: (1) a gas consisting primarily of hydrogen, methane, carbon monoxide, and carbon dioxide; (2) a "tar" or "oil" that is liquid at room temperature and includes organic chemicals such as acetic acid, acetone, methanol; and (3) a "char" consisting of almost pure carbon plus any inerts (glass, metals, rock) that enter the process. Kaiser suggests a reaction for decomposition of cellulose ($C_6H_{10}O_5$) undergoing pyrolysis as follows:

$$3(C_6H_{10}O_5) \rightarrow 8H_2O + \text{"}C_6H_8O\text{"} + 2CO + 2CO_2 + CH_4 + H_2 + 7C$$

where "C_6H_8O" represents the family of liquid products obtained in pyrolysis.[56] While cellulose is the major reactant in pyrolysis of solid wastes, other organic materials will also pyrolyze. The relative fractions of the various organic constituents would, of course, affect the yield of products. Batch retort experiments conducted at San Diego indicate that product breakdown is strongly dependent upon temperature.[57] This suggests that a great many parallel reactions are occurring.

CURRENT APPLICATIONS OF PYROLYSIS TO SOLID WASTE

Pyrolysis is an advanced waste treatment technique, and, consequently, applications to solid waste are extremely limited. References to pyrolysis of solid waste illustrate the state of this very interesting process. A paper by Porteous discusses pyrolysis of solid waste to make acetone, acetic acid, charcoal, and salable tars and oils.[58] Laboratory scale experiments on the pyrolysis of solid waste are being conducted at New York University and by the Utilities Department of the City of San Diego.[57,58] Two pilot scale devices are also in operation. The first of these is operated by Cameron-Yakima, Inc., at Yakima, Washington,[59] and the second by the Waste Conversion Systems Division of Pan American Resources, Inc., located in Albuquerque, New Mexico. As reported in *Chemical Engineering* and from personal contact, the Cameron-Yakima unit has been tested on a variety of specific wastes, but not on municipal refuse *per se*.[60,61] The Lantz Converter of Pan American Resources, on the other hand, is apparently the only pyrolysis system designed for and tested upon mixed municipal refuse, although it has been applied to a variety of specialty wastes as well.

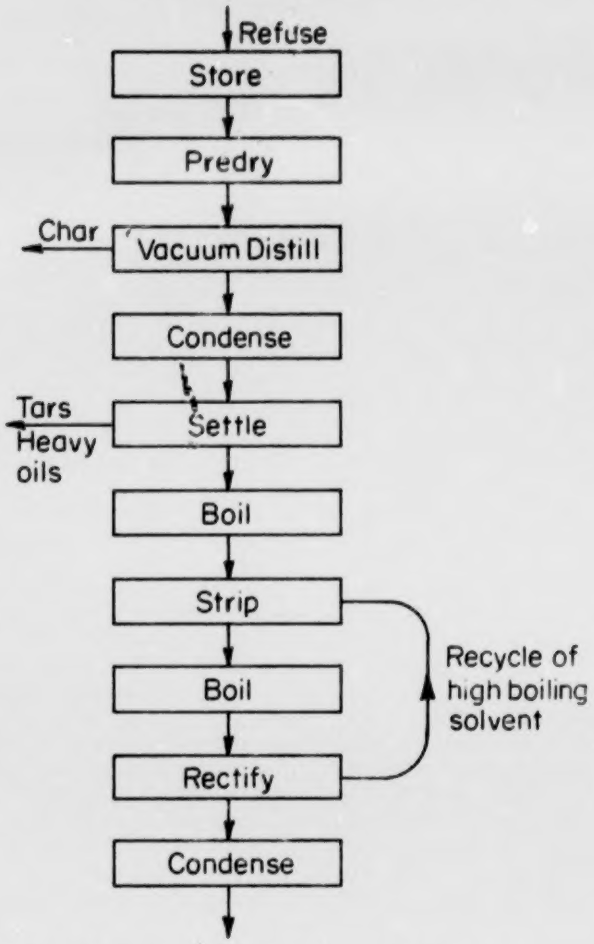

FIGURE 69. *Flow diagram, acetic acid from refuse.*[58]

An attempt has been made above to list the more interesting ongoing pyrolysis work in order of chronological distance from actual application to municipal solid waste. As with any new technology, there is a large disparity in the results, ranging from extremely unfavorable (Porteous) to extremely favorable (Lantz Converter). Since the Lantz Converter is being marketed as a potential waste disposal system in which only the service is sold, detailed data on feed and product analysis, performance, and equipment design are not available for publication. Some limited cost data have, however, been obtained. Detailed analytical data are available from the San Diego pyrolysis work, but these are from small-scale batch retorts and the data may not be directly applicable to larger continuous units. Specific information from ongoing pyrolysis work is discussed in the following sections.

Paper Evaluation of Pyrolysis. A cost analysis of pyrolysis as a process for municipal solid waste disposal is given by Porteous.[58] Since this effort was a paper study only, equipment for the process was designed and cost estimates made in consultation with a leading manufacturer in the field. The refuse is compressed into bales 3 ft in diameter by 5 ft in length with a dry density of 30 lb per cu ft. These bales are predried and destructively distilled in vacuum retorts, 3½ ft in diameter by 30 ft in length, producing noncondensable gases, condensed liquids, and char. The noncondensable gases are burned for process heating, and the char is quenched, briquetted, and sold. The condensate is separated into heavy and light fractions. The heavy fraction is sent to a tar still to yield creosote and a phenolic agglomeration, or is burned for process heat. The acetic acid is stripped from the oils in the vapor phase of the lighter fraction using a suitable high-boiling solvent. The acetic acid is then separated from the solvent by vacuum distillation to yield commercial-grade acetic acid (Figure 69).

The cost breakdown was estimated

TABLE 33

REVENUE ESTIMATE FOR PYROLYSIS [58]

Item	Yield (percent)	Ton per day	Price	Revenue (per diem)
Acetone	0. 3	0. 45	6.5¢/lb	$57
Acetic acid	3. 1	4. 65	9¢/lb	835
Tars	7	10. 5	1¢/lb	360
Oils	5	7. 5		
Charcoal	25	37. 5	$7/ton	260
				$1, 512

based on 1967 prices and the process appeared to be a highly unprofitable operation costing about $5.70 for each ton of raw refuse (Tables 33 and 34). This process is, by design, directly analogous to destructive distillation of wood even to the extent that refuse is compressed into large blocks before processing. Much of the processing cost is tied up transporting heat and mass to and from this large compressed block; a retort residence time of 23 hr is required to effect destructive distillation.[58] While design of a better pyrolysis process is beyond the scope of this report, it seems likely that greater efficiency would be possible if the process was designed exclusively for the treatment of solid wastes.

Retort Research on the Pyrolysis of Municipal Waste. Two experimental programs on the pyrolysis of solid waste are being conducted under research grants of the Bureau of Solid Waste Management. The first of these (Grant No. SW 00043–03) is being directed by Kaiser at New York University.[56] This work has included measurement and analysis of pyrolysis gases obtained from various organic components of municipal refuse including paper, wood, grass, leaves, and food wastes.[56, 59] Work has also been initiated on pyrolyzing mixed refuse and operating a continuous pilot-scale

TABLE 34

COST ESTIMATE FOR PYROLYSIS [58]

Plant cost	$8,000,000
Fixed charges at 0.1030*	824, 000
Labor, 12 men at $7, 000	84, 000
4 men at $9,000	36, 000
Maintenance (2% retort investment) †	190, 000
Disposal 149T residual refuse/day at $4.50/ton	245, 000
Total cost	1, 065, 000
Revenue at $1,521/day	550, 000
Net annual cost	515, 000
Disposal cost/ton	$5. 66

*Original paper assured 20-year plant life at 4 percent interest. These figures were changed to 15 years and 6 percent, respectively.

†Data obtained on hammermill operation indicated maintenance costs of the order of $1.00/ton processed could be expected. Approximately $90,000 was, therefore, added to Porteous' maintenance figure.

TABLE 35

SAN DIEGO SANITARY FILL MATERIAL SURVEY [57]

(Started July 30, 1965—Completed March 25, 1966)

	Total material (percent)	
	As received	Range during survey
Combustibles	50.27	55.51–43.72
Incombustibles	49.73	56.28–46.33

Combustible portion (percent)

Constituent	As received	Range during survey	Moisture ASTM D271–58	Dry basis	
				With metal and glass	Without metal and glass
Paper	46. 16	50. 55–40. 99	8. 23	42. 36	50. 40
Yard trimmings	21. 14	26. 65–20. 78	51. 30	10. 30	12. 25
Wood	7. 48	8. 10–4. 41	10. 50	6. 69	7. 96
Rags	3. 46	4. 07–0. 32	7. 40	3. 20	3. 82
Rubber	4. 73	4. 76–3. 60	9. 74	4. 27	5. 08
Plastic	0. 27	0. 52–0. 25	0. 06	0. 27	0. 32
Garbage	0. 81	0. 92–0. 77	57. 80	0. 34	0. 40
Metal	7. 64	9. 68–6. 30	0	7. 64	0
Glass	8. 31	10. 38–7. 67	0	8. 31	0
Moisture				16. 62	19. 77
Total	100. 00			100. 00	100. 00

TABLE 36

PYROLYSIS PRODUCT YIELD[17]

Temp (F)	Refuse (lb*)	Gases (lb)	Pyroligneous acids and tars (lb†)	Char (lb)	Mass accounted for (lb)
900	100	12. 33	61. 08	24. 71	98. 12
1200	100	18. 64	18. 64	59. 18	99. 62
1500	100	23. 69	59. 67	17. 24	100. 59
1700	100	24. 36	58. 70	17. 67	100. 73

*On an as-received basis, except that metals and glass have been removed.
†This column includes all condensables and the figures cited include 70 to 80 percent water.

TABLE 37

PROXIMATE ANALYSIS OF PYROLYSIS CHAR[17]

Percent	Pyrolyzing temperatures (F)				
	900	1,200	1,500	1,700	Pennsylvania anthracite
Volatile matter (percent)	21. 81	15. 05	8. 13	8. 30	7. 66
Fixed carbon (percent)	70. 48	70. 67	79. 05	77. 23	82. 02
Ash (percent)	7. 71	14. 28	12. 82	14. 47	10. 32
Btu per lb	12, 120	12, 280	11, 540	11, 400	13, 880

TABLE 38

GASES EVOLVED BY PYROLYSIS[17]

Constituent	Percent by volume at indicated temperatures (F)			
	900	1,200	1,500	1,700
H_2	5. 56	16. 58	28. 55	32. 48
CH_4	12. 43	15. 91	13. 73	10. 45
CO	33. 50	30. 49	34. 12	35. 25
CO_2	44. 77	31. 78	20. 59	18. 31
C_2H_4	0. 45	2. 18	2. 24	2. 43
C_2H_6	3. 03	3. 06	0. 77	1. 07
Accountability	99. 74	100. 00	100. 00	99. 99

refuse gasifier. Data are not yet available from these portions of the program.

The city of San Diego, California, has been conducting small-scale research on pyrolysis of solid waste. The work, partially funded under a grant from the Bureau of Solid Waste Management (Grant No. SW 00036-02), has resulted in significant advances in the analysis of the products from pyrolysis of municipal solid waste as well as information on process heat balances. Typical San Diego municipal waste was fed to a retort in which pyrolysis was conducted (Table 35). The glass and metal were removed before the start of the pyrolysis experiments. These experiments were conducted in a retort containing approximately 0.4 lb of refuse. The condensable liquids were captured in a series of cooled traps and the gaseous products in a gas balloon. Pyrolysis experiments on the typical San Diego waste were run at temperatures from 900 to 1,700 F. The amount of char and condensables were determined gravimetrically, and the pyrolysis gases were measured by volume (Table 36). Qualitative analyses were made on the condensable fraction to identify the organic compounds present. A proximate analysis of the char portion was obtained, and the gas phase was analyzed quantitatively by means of a gas chromatograph (Tables 37 and 38).

As pointed out, no quantitative analyses have yet been made of the "pyroligneous acid" (i.e., condensable) phase. Qualitatively, in addition to water, the condensable phase includes methanol, ethanol, isobutanol, n-pentanol, tert-pentanol, 1,3-propanediol, 1-hexanol, and ascetic acid.

There are a number of alternative paths that can be considered in attempting to employ pyrolysis as a process for the recovery of solid waste. As discussed earlier, Porteous directed his paper evaluation toward the manufacture of acetic acid from the condensable phase.[55] Another, and perhaps more direct, approach is to utilize the products of pyrolysis to provide the thermal energy required for the process. One of the most significant results of the San Diego pyrolysis

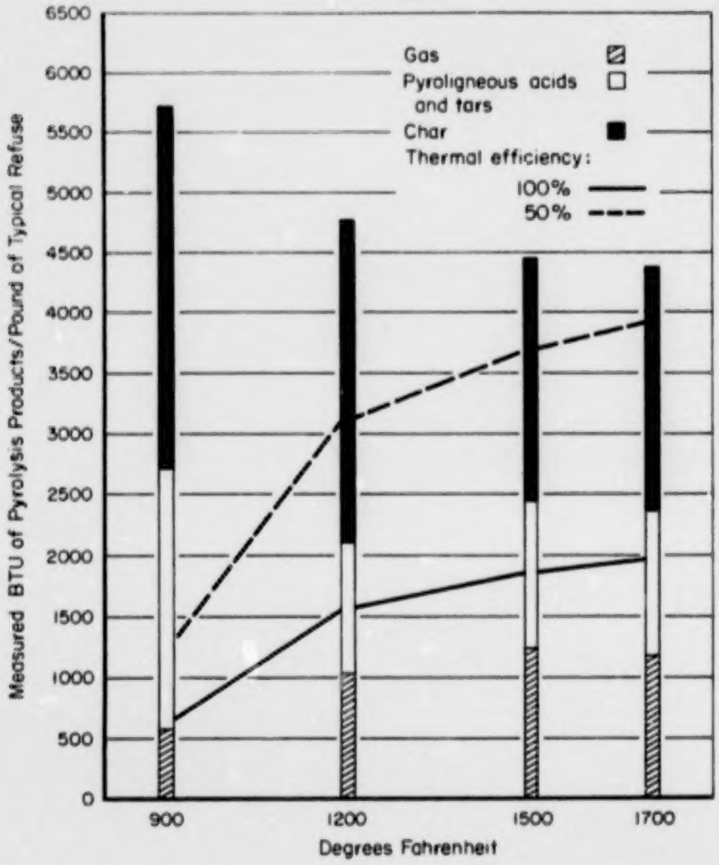

FIGURE 70. ***Pyrolysis per lb of typical refuse.***[57] ***Measured energy of products is plotted against energy required to sustain process.***

experiments was measurement of the heat content of the products of pyrolysis and evaluation of these in terms of the heat required to sustain the process (Figure 70). For a realistic thermal efficiency of 50 percent, only pyrolysis at 900 F is self-sustaining unless the energy content of the char is also employed to provide additional heat to the process. It should be noted that the San Diego pyrolysis work is now moving out of batch processes and into a continuous device. Preliminary unpublished data indicate that the self-sustaining potential of a continuous pyrolysis unit is much greater than one would conclude from batch work. These fragmentary data, if verified, would confirm the claims for privately operated pyrolysis units* in which the gas and condensable product are reported to be more than sufficient to sustain the process.

Operating Pyrolysis Units for Waste Disposal. E. C. Cameron of Yakima, Washington, has applied for a patent on a device that pyrolyzes organic wastes at 2,000 F in a low-pressure (4 to 7 psig) steam environment.[61] The unit has been used to demonstrate processing of various organic wastes including wood, rubber tires, photographic film, etc. A variety of carbon products are recoverable including coke, lampblack, or charcoal, depending on the nature of the feed material. Specialty items such as silver (from the processing of photographic film) have also been recovered. The system is designed so that the condensable overloads can be recovered and used to fire the retort. No mention was made of the noncondensable gases, but these are apparently lost with this process. Although pilot-scale units have been employed to convert a variety of wastes to carbon, little data are available on the system. Published information is limited to a brief news item in *Chemical Engineering* and a patent application.[60] The above information is based on these sources and supplemented by letter and personal contact with the inventor of the device.[61]

The most completely developed device for pyrolyzing municipal waste is the Lantz Converter. This device was patented in 1961 by a private inventor, is on the market,[62]† and represents the most advanced application of the principle of pyrolysis to the processing of municipal waste. Lantz Converters have been quoted with input ranging from ¼ to 12 tons per hr, although the largest unit constructed to date is rated at 2 tons per hr.

The Lantz Converter is basically a pyrolysis unit in which mixed municipal refuse is fed continuously through a hammermill to a revolving stainless steel drum. The process is initiated using natural gas to bring the equilibrium temperature up to 2,000 F in the absence of air. As pyrolysis takes place, the "off-gases" (condensable and noncondensable) are fed back into the gas burners in a self-sustaining process. According to Pan American Resources, Inc., only about 70 percent of the off-gases are required to maintain the pyrolysis temperatures. At this time, the excess off-gases are flared and only charcoal recovery has been explored. Eventual usage of the off-gases not required to sustain combustion is contemplated. However, since the Lantz Converters are not sold as equipment *per se*, little specific data on cost of operation are available. Company brochures furnished the only basis for cost estimates and these were overall capital equipment costs for units of ¼ and 12

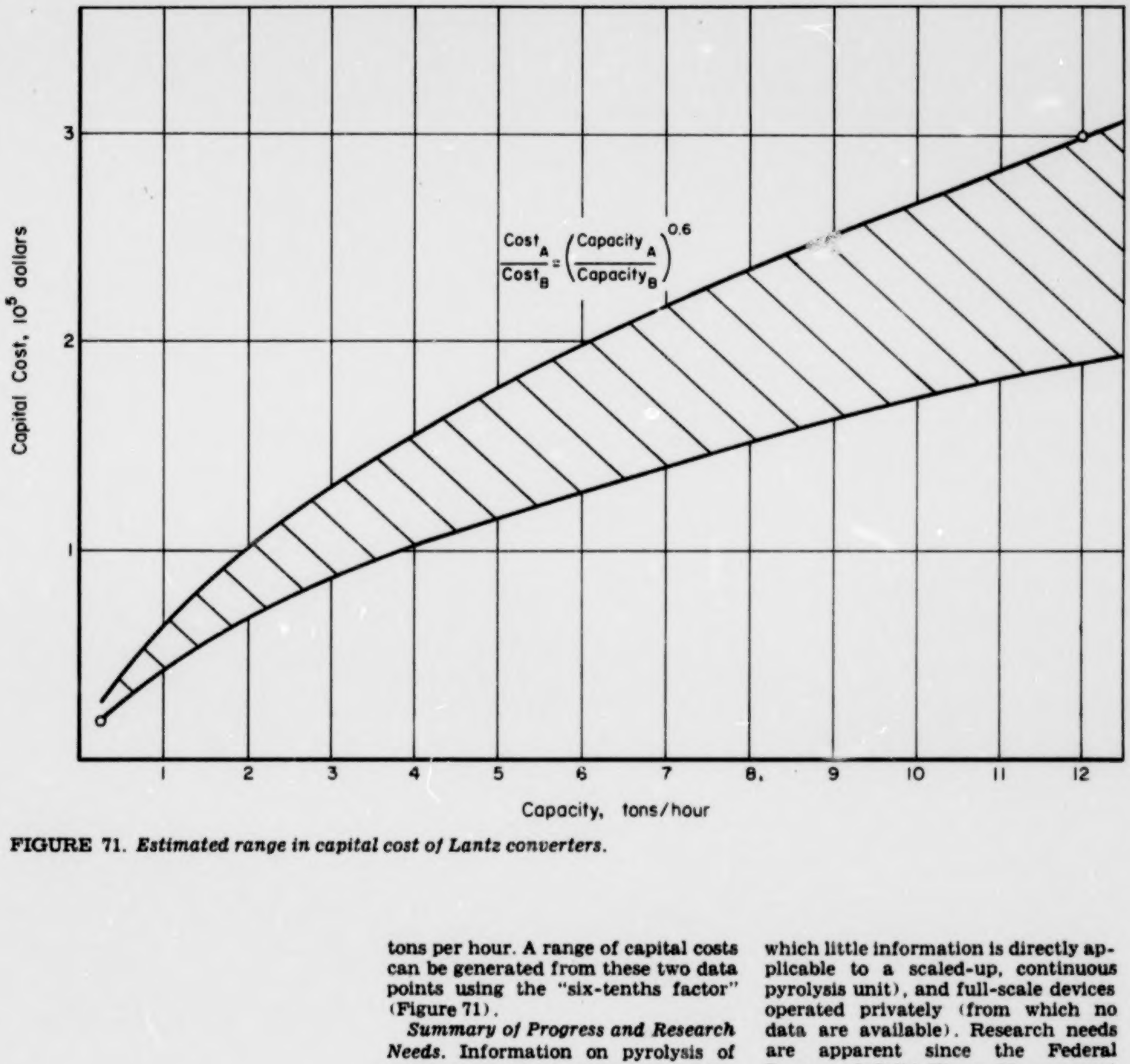

FIGURE 71. *Estimated range in capital cost of Lantz converters.*

tons per hour. A range of capital costs can be generated from these two data points using the "six-tenths factor" (Figure 71).

Summary of Progress and Research Needs. Information on pyrolysis of cellulose has been accumulated by the charcoal and wood chemical industries. With the exception of charcoal, production of other materials from pyrolysis of wood has proved to be only marginally successful. However, coupling the concept of pyrolysis with a true waste product that has no present market value may prove to be economically attractive. Progress to date on the pyrolysis of refuse has proceeded down two parallel, but widely separated, paths: laboratory batch processes (in which detailed scientific data are taken, but from which little information is directly applicable to a scaled-up, continuous pyrolysis unit), and full-scale devices operated privately (from which no data are available). Research needs are apparent since the Federal Bureau of Solid Waste Management sponsored laboratory tests have indicated a promising potential for this method. The primary research need at this point is for a pilot or full-scale pyrolysis system (½- to 1-ton per hr) including associated gas, condensable, and charcoal recovery systems; appropriate feed preparation devices (size reduction, drying, etc.) should also be provided. To ensure that heat and mass balances as well as reaction rates are closely monitored as the system operates, continuous chemical and thermal data should be taken.

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*See the following section for a discussion of the "Lantz Converter."

†Lantz Converter Division of Pan American Resources, Inc., of Albuquerque, New Mexico.

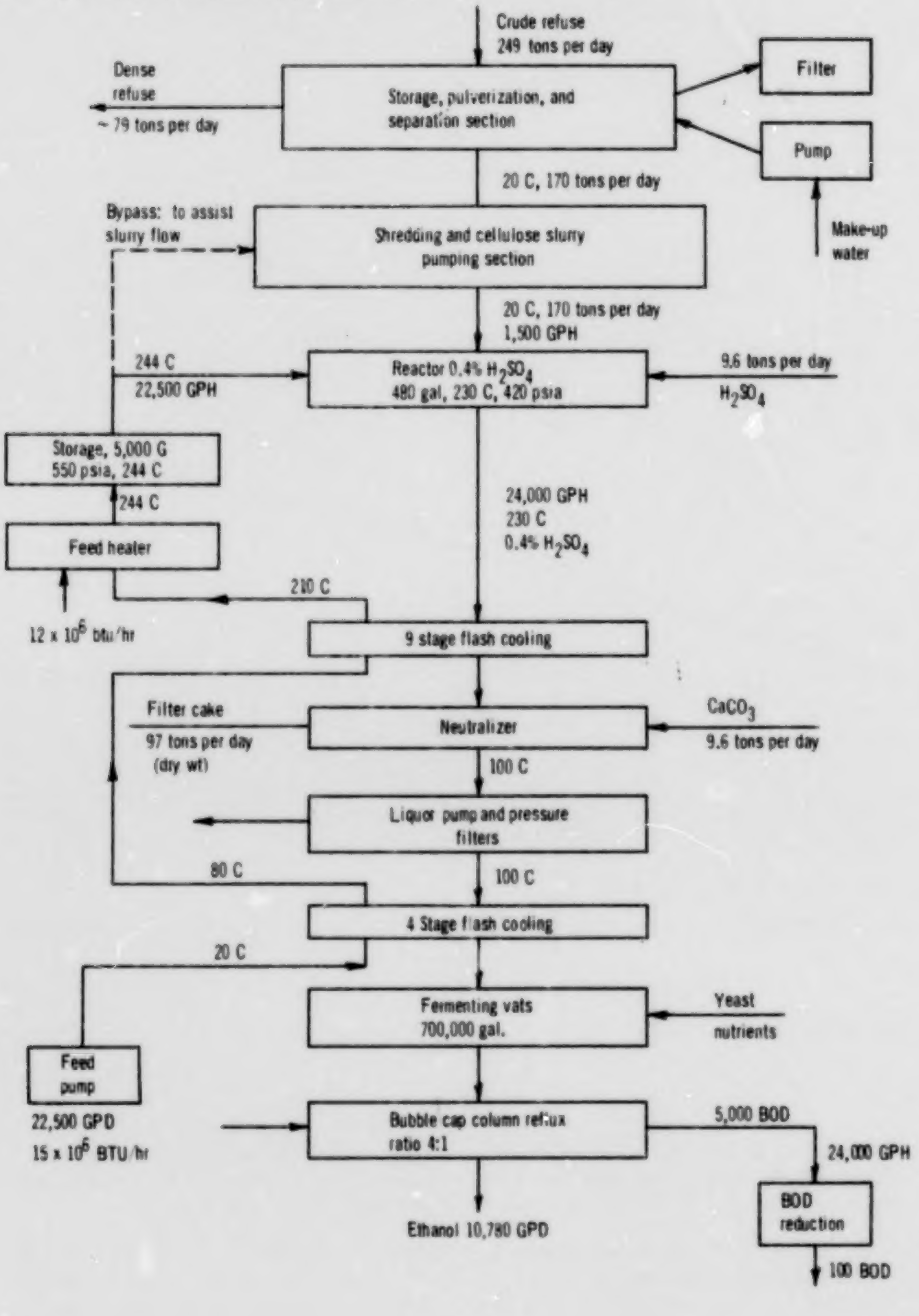
Crude refuse
249 tons per day
Dense refuse
~ 79 tons per day
Storage, pulverization, and separation section
Filter
Pump
Make-up water
20 C, 170 tons per day
Bypass: to assist slurry flow
Shredding and cellulose slurry pumping section
20 C, 170 tons per day
1,500 GPH
244 C
22,500 GPH
Reactor 0.4% H2SO4
480 gal, 230 C, 420 psia
9.6 tons per day
H2SO4
Storage, 5,000 G
550 psia, 244 C
244 C
Feed heater
12 x 10^6 btu/hr
24,000 GPH
230 C
0.4% H2SO4
210 C
9 stage flash cooling
Filter cake
97 tons per day
(dry wt)
Neutralizer
CaCO3
9.6 tons per day
100 C
Liquor pump and pressure filters
80 C
100 C
4 Stage flash cooling
20 C
Fermenting vats
700,000 gal.
Yeast
nutrients
Feed pump
22,500 GPD
15 x 10^6 BTU/hr
Bubble cap column reflux ratio 4:1
5,000 BOD
24,000 GPH
BOD reduction
100 BOD
Ethanol 10,780 GPD

FIGURE 72. *Process flow sheet, continuous ethanol production from refuse.*[58]

In summary, the concept of pyrolysis applied to solid waste is new, but can, on the basis of available information, be considered one of the more promising advanced techniques for waste management because (1) laboratory results indicate that a wide variety of valuable products (including producer gas, acetic acid, methanol, and charcoal) can be simultaneously produced; (2) relatively large pyrolysis units have been built privately and operated with reported success; and (3) the process has the potential of being self-sustaining.

HYDROLYSIS

Of the many possible chemical reactions that can be considered for solid waste utilization, one of the most interesting is the hydrolysis of cellulose, the major chemical constituent of municipal refuse. As in pyrolysis, the historic background is in the hydrolysis of wood, specifically the "Madison Wood Sugar Process" that was developed at the U.S. Forest Products Laboratory at Madison, Wisconsin during World War II.[illegible]

The specific reaction involved in cellulose hydrolysis is:

$$\underset{\text{(cellulose)}}{C_6H_{10}O_5+H_2O} \xrightarrow{H_2SO_4} \underset{\text{(glucose)}}{C_6H_{12}O_6}$$

where the dilute (0.5%) sulfuric acid acts only as a catalyst. Various other sugars and sugar products also are formed as by-products and much effort has been expended to minimize these side reactions. Sugar is no longer produced from wood in this country because it can be obtained more economically and conveniently from other sources. However, as with pyrolysis, when the source of cellulose is municipal refuse, hydrolysis may have a more favorable economic basis because of the "negative value" of the major raw material.

Hydrolysis of cellulose resulting in a dilute glucose solution is of little value unless it is considered in conjunction with other processes. The Madison Wood Sugar process, for example, includes neutralization of the sugar-bearing acid solution followed by fermentation to produce ethyl alcohol. Another approach is to initiate biological activity in the sugar solution under aerobic conditions to promote digestion of the sugar with a resultant large increase in the yeast population. This latter process is directed toward producing protein for animal feeds. Consequently, the costs and flow charts for the hydrolysis step are discussed in conjunction with the overall processes for solid waste utilization.

PRODUCTION OF ETHYL ALCOHOL FROM MUNICIPAL REFUSE

Ethyl alcohol may be manufactured from four general types of raw material: (1) sugar-bearing materials (sugar cane, etc.), (2) starchy materials (grains, etc.), (3) hydrocarbon gases (e.g., ethylene), and (4) cellulosic materials.[illegible] Traditionally, most ethyl alcohol for both beverage and industrial use has been manufactured by fermentation of natural materials in the sugar-bearing and starch categories. In recent years, however, synthetic ethyl alcohol manufactured by the esterification of ethylene has displaced ethyl alcohol from fermentation as the major source of industrial alcohol. Such synthetics, by law and/or custom, cannot be used to manufacture alcohol for beverage use or for certain solvent uses. Ethyl alcohol manufactured from cellulose would be similarly restricted.

The manufacture of ethyl alcohol from cellulose, the fourth raw-material source listed above, is predicated upon the hydrolysis of cellulose to sugar (glucose) as discussed earlier. Fermentation of the glucose to ethyl alcohol is written as follows:

$$\underset{\text{(glucose)}}{C_6H_{12}O_6} \xrightarrow{\text{yeast}} \underset{\text{(ethyl alcohol)}}{2C_2H_5OH} + 2CO_2$$

As in the case of hydrolysis, troublesome side reactions should be minimized. In addition, the yeast and fermenting conditions (temperature, pH, etc.) must be carefully controlled.

MADISON WOOD SUGAR PROCESS

Pilot-scale and commercial operations on the hydrolysis of wood followed by fermentation to produce ethyl alcohol were conducted at Madison, Wisconsin, and Springfield, Oregon, during and immediately after World War II.[illegible] Production was terminated at both facilities by the middle of 1947. The full-scale operation at Springfield hydrolyzed 221 tons per day of sawmill waste and produced *in toto* approximately 50,000 gal of ethyl alcohol before the lease was surrendered to the Reconstruction Finance Corporation in 1947. The production costs at that time were estimated to be $0.30 to $0.35 per gal.[illegible] Commercial-grade ethyl alcohol is currently selling for $0.52 per gal.[illegible]

PRODUCTION OF ALCOHOL FROM MUNICIPAL REFUSE—A PAPER EVALUATION

Based on the Madison Process and certain technical considerations of cellulose chemistry, Porteous conceived a process for the hydrolysis of mixed municipal refuse followed by fermentation to produce ethyl alcohol.[illegible]

This process includes storage, "pulverizing," and separation of raw municipal refuse, as well as all associated processes included in the hydrolysis, fermentation, and distillation of ethyl alcohol from the refuse (Figure 72). The separating process (Figure 72) includes "pulverizing" (in an undesignated manner) followed by flotation separation by water to yield a dense stream (to landfill) and a light fraction with the concentrated cellulose.

A cost analysis of the process based on a 60 percent cellulose content in the feed was made by Porteous and revised slightly by Battelle (Table 39). The cost data indicate that a combined hydrolysis/fermentation plant to process 249 tons per day of refuse might be constructed for approximately $2,300,000. The plant would produce about 4 million gal of alcohol annually and return a profit of $2.50 per ton of refuse processed. An alcohol selling price of only $0.40 [illegible] gal was assumed, compared with a cur[illegible] market price of over $0.50 per gal. However, since these figures are not based on experimental work no firm statements can be made about their validity. On the basis of available data, however, the economics appear to be more favorable than any other process. A further discussion of the economics of this process may be found in the following section.

Summary of progress and research needs. Even though the production of alcohol from wood was achieved at less than the market prices and with only minor processing difficulties, the fact remains that production of alcohol from wood ceased in 1947 and has not been resumed. The work reported above indicated a favorable economic base for the production of ethyl alcohol from municipal solid wastes,[illegible] but

TABLE 39

ECONOMIC ANALYSIS OF ETHANOL PRODUCTION FROM MUNICIPAL REFUSE CONTAINING 60 PERCENT CELLULOSE[illegible]

Plant cost	$2, 262, 000	
Annual costs:		
Fixed charges at 0.1030*	233, 000	
Maintenance (2% equipment cost)†	110, 000	
Material cost, including power	305, 000	
Labor	156, 000	
Disposal of 176 tons/day of residual refuse	280, 000	
Reduction of 23,500 lb/day BOD	258, 000	
Total cost per yr	$1, 340, 000	
Annual revenue:		
3.93×10^6 gal ethyl alcohol at 40¢/gal	$1, 570, 000	
Annual profit	230, 000	
Profit per ton refuse		2. 50

*Original paper assumed 20-yr plant life at 4 percent interest. These figures were changed to 15 yr and 6 percent, respectively.

†Data obtained on hammermill operation indicated expected maintenance costs in the order of $1.00 per ton processed. Approximately $90,000 was, therefore, added to Porteous's maintenance figure.

TABLE 40

PRODUCTION COST IN CENTS PER LB SUGAR FOR VARIOUS RAW WASTE COMMODITIES AND VARIOUS PLANT CAPACITIES*

Raw material type	Price (per ton)	Plant capacities (tons per day)				
		80	150	300	500	1,000
No. 1 mixed wastepaper	4.00	4.39	3.76	3.20	2.91	2.59
	12.00	5.42	4.80	4.22	3.93	3.62
Bagasse	5.00	4.53	3.90	3.33	3.03	2.73
	15.00	5.81	5.18	4.60	4.32	4.01
Organic urban refuse	2.50 Cr	3.56	2.93	2.36	2.07	1.76
	4.50 Cr	3.30	2.68	2.11	1.81	1.51
Mixed urban refuse†	2.50 Cr	4.19	3.39	2.69	2.34	1.96
	4.50 Cr	3.94	3.13	2.44	2.08	1.71

*Basis: three-stage continuous plant.
†Includes hydrapulper operation.

the cost figures are preliminary and should be viewed with caution. Serious questions must be raised regarding the costs of the process. Specifically, it was noted that the cost estimate for size reduction appeared to be low. Of even more concern is the apparent discrepancy in costs estimated by Porteous and by Ionics, Inc.[68] Cursory examination of capital and operating costs for similar portions of the two processes (both employ hydrolysis) indicates an almost two-fold difference. The Porteous process was on the low side, despite the fact that many conservative features were built into the cost estimates. Among these are: data from wood hydrolysis were used in the calculation (whereas paper and refuse may react more quickly), and the break-even point for alcohol production is taken at $0.40 per gal (whereas the market price has remained around $0.52 per gal for the past several years).

The production of ethyl alcohol from wood proved to be at least marginally economic, and first estimates of the process applied to municipal solid waste appear favorable. It is recommended that research be conducted: to evaluate in detail the economics of the process, using as a basis ongoing data from the Federal Office of Solid Waste Management sponsored work[illegible]; and, if these results still indicate favorable economics, to proceed with a pilot-scale demonstration of the manufacture of ethyl alcohol from mixed municipal solid waste.

PRODUCTION OF PROTEIN FROM SOLID WASTE

Conversion of waste paper to protein. The Denver Research Institute, Denver, Colorado, is attempting to convert waste paper to protein using a fast-growing hydrocarbon-cellulose-digesting organism having a high chemical or protein score (PHS Grant No. UI00565–01). The process includes fermentation of waste paper in water enriched with hydrocarbons, oxygen, and nitrogen. The resultant protein product would be utilized for livestock feed. Little information is available on this project which is in its first year, but following microbe selection, future work will include optimization of the process, pilot-scale testing, and feeding studies.

Evaluation of a process to culture yeast on solid waste: a report of the work of Ionics, Inc. The most detailed cost evaluation of any of the advanced chemical conversion methods for solid waste is in a report by Ionics, Inc., to the Public Health Service (Contract No. PH 86–67–204). In this study, detailed costs estimates and limited process optimizations were prepared for a hydrolysis-fermentation plant producing yeast.[68]

The hydrolysis portion of this process includes four processing steps: hydrolysis, flash vaporization, neutralization, and centrifugation. The recommended plant utilized the hydrolysis reactors in series and was assumed to operate on a continuous basis.

Four possible feed materials were considered for the hydrolysis plant: No. 1 mixed wastepaper, bagasse, organic urban refuse (i.e., no cans, bottles, etc.), and mixed urban refuse.

In the cost analyses, a range of commodity prices was considered for the No. 1 mixed wastepaper and the bagasse, whereas a dumping credit was taken for both organic and mixed urban refuse. For the mixed urban refuse, moreover, a feed-preparation penalty was imposed in the form of an additional equipment item (a Black Clawson hydropulper). The cost to produce sugar in the hydrolysis operation was determined as a function of plant input and raw materials (Table 40).

The neutralized sugar solution from the hydrolysis process is fed into a fermenting process where, under aerobic conditions, the organism *Candida utilis* is cultured. Costs for the fermentation process were calculated on two bases: (1) maximum-cost plant, utilizing a metal fermentor and a refrigeration-cooling tower system; and (2) minimum-cost plant, using wooden construction for the fermentor and a local surface water source for cooling. The cost of producing yeast was determined for feed rates ranging from 80 to 1,000 tons per day (Table 41).

TABLE 41

YEAST PRODUCT COSTS VERSUS PLANT SIZE[68]

Plant size* (ton per day)	Product cost for yeast (cents per lb)†	
	Maximum cost plant	Minimum cost plant
80	9.22	5.96
150	7.78	------------
300	6.60	------------
500	5.70	3.96
1000	5.00	------------

* Basis: feed to hydrolysis plant.
† These figures do not include the cost of the hydrolysate sugars.

On the basis of the sugar production costs (Table 40), the yeast costs (Table 41), and the percent protein in the *C. utilis* yeast, the cost of protein production can be calculated for any size plant. These costs can then be compared with protein prices from other sources. For a 500-ton-per-day plant, assuming a 50 percent sugar to yeast utilization factor, the cost of producing protein from urban refuse appears competitive (Table 42).

It is expected that research on the process will now proceed from the current paper study to an experimental program.

GENERAL CHEMICAL METHODS OF SOLID WASTE CONVERSION

The potential for chemical conversion of solid waste is almost unlimited, at least in terms of the processes that can be considered. Pyrolysis and hydrolysis-fermentation represent processes that have been demonstrated at least on a pilot scale, or have a wood-chemical counterpart, or have had

TABLE 42

SUMMARY PROTEIN COSTS VERSUS ALTERNATE ANIMAL FEEDS[66]

Protein source	Percent protein	Cost/lb protein
Soy bean meal	44	8. 0–14. 8
Animal meal	50	8. 2–12. 6
Fish meal	60	10. 5–14. 2
Torula yeast (*Candida utilis*):	55	
Sulfite waste liquor		27–29
Bagasse		18. 2–26
Wastepaper		17. 8–24. 7
Mixed urban refuse		14. 7–18. 9
Organic urban refuse		13. 8–17. 8

extensive economic evaluations. None of the other work in chemical conversion has progressed beyond paper or preliminary laboratory studies. Two additional approaches for chemical conversion of solid waste are suggested.

Partial oxidation of solid organic wastes. Research is being conducted at Rensselaer Polytechnic Institute, Troy, New York, on the partial oxidation of organic wastes in a heated fluidized bed.[69] The process closely resembles the pyrolysis processes discussed earlier, except that oxygen is controlled rather than eliminated and the reaction takes place in a fluidized bed. As in pyrolysis, partial oxidation produces a variety of organic gases and condensables that can be captured in a series of traps and analyzed. To date, only wastepaper has been processed in laboratory scale experiments; evidence indicates that methane, acetic acid, formaldehyde, and formic acid have been produced.

Work on this project is continuing at Rensselaer under PHS Grant No. UI 00552–02 and will be extended to include materials other than paper. The goal of the program is, of course, to develop this technique to produce economically salable organic products. Because of the basic nature of the work to date, no cost information is available.

Chemical transformation of solid waste. A literature and laboratory program being conducted at Oregon State University under PHS Grant No. UI 00510–02 includes almost all possible chemical reactions applicable to solid waste conversion. Thus far, chemical reactions with straw, dust bark, and transformed municipal solid waste (compost); the markets and uses for cellulose and solid waste; and the hydrogenation of cellulose have been studied. Recent experimental work in this project has included increasing the nitrogen, phosphorus, and sulfur content of cellulosic materials to enhance their values as solid amendments or as feeds for ruminants. Results of the investigations to date provide an almost complete catalog of possible chemical reactions for the cellulosic materials in solid waste.

FLY-ASH UTILIZATION

This discussion outlines recent trends in the technical and economic aspects of coal fly-ash utilization and assesses the utility of incinerator fly ash in similar applications. A wide range of potential uses exists, but many technical and economic obstacles must be overcome before widespread use becomes a reality.

Since there is no experience with the utilization of fly ash from municipal incinerators in the United States, any discussion must rely heavily upon experience with utilization of coal fly ash. A short discussion will put the subject into perspective, but for additional details, the reader is referred to the proceedings of a conference sponsored jointly by the Edison Electric Institute, the National Coal Association, and the U.S. Bureau of Mines.[70]

When pulverized coal is burned, fly ash is formed from the noncombustible components of the coal and unburned particles of coal that result from incomplete combustion. The considerable variation in fly-ash properties is a contributing factor to its limited reutilization. Average particle size ranges from 1 to 80 microns. A similarly wide range occurs with respect to particle shape, density, color, and chemical properties. The chemical composition of most fly ash is more than 85 percent alumina, silica, iron oxide, lime, and magnesia, with the percentage of any one component varying widely (Table 43).

Traditional uses for fly ash have been as an additive to replace another, presumably more costly, material in a given application. Most of these applications require a fly-ash conforming to established specifications. The cost of processing fly ash to meet these specifications is a significant factor governing the economics of reutilization. However, a new brickmaking process being developed by the Coal Research Bureau may tolerate loosely specified fly ash and may eliminate this limitation.

Electric utilities produce about 20 million tons of coal fly ash each year, but only an estimated 1.5 million tons are reused.[71] This limited use is a result of (1) a lack of basic knowledge concerning the factors that govern fly-ash performance in a given application; and (2) economic factors (fly ash must compete with other readily available, rather low-cost, high-quality products).

UTILIZATION OF COAL FLY ASH

Concrete additive. Perhaps the greatest single application of fly ash is in concrete and concrete products. An example is the Hungry Horse Dam on the Flathead River in Montana, which required 3,086,000 cu yd of concrete and contained 126,000 tons of fly ash, at an estimated savings of $1,500,000 in material cost.[72]

Mixed with concrete, fly ash serves two primary purposes. First, it may serve as a filler to balance aggregate particle size distributions. Second, as a pozzolanic material it reacts chemically with lime to form a cementitious material which increases the strength of the concrete. The mechanisms whereby fly ash effects changes in concrete properties, such as strength,

TABLE 43

RANGES OF CHEMICAL COMPOSITION OF U.S. FLY ASH[72]

Constituent	Range (percent by weight)
Silica (SiO_2)	34–48
Alumina (Al_2O_3)	17–31
Iron oxide (Fe_2O_3)	6–26
Calcium oxide (CaO)	1–10
Magnesium oxide (MgO)	0. 5–2
Sulfur trioxide (SO_3)	0. 2–4
Unburned material	1. 5–20

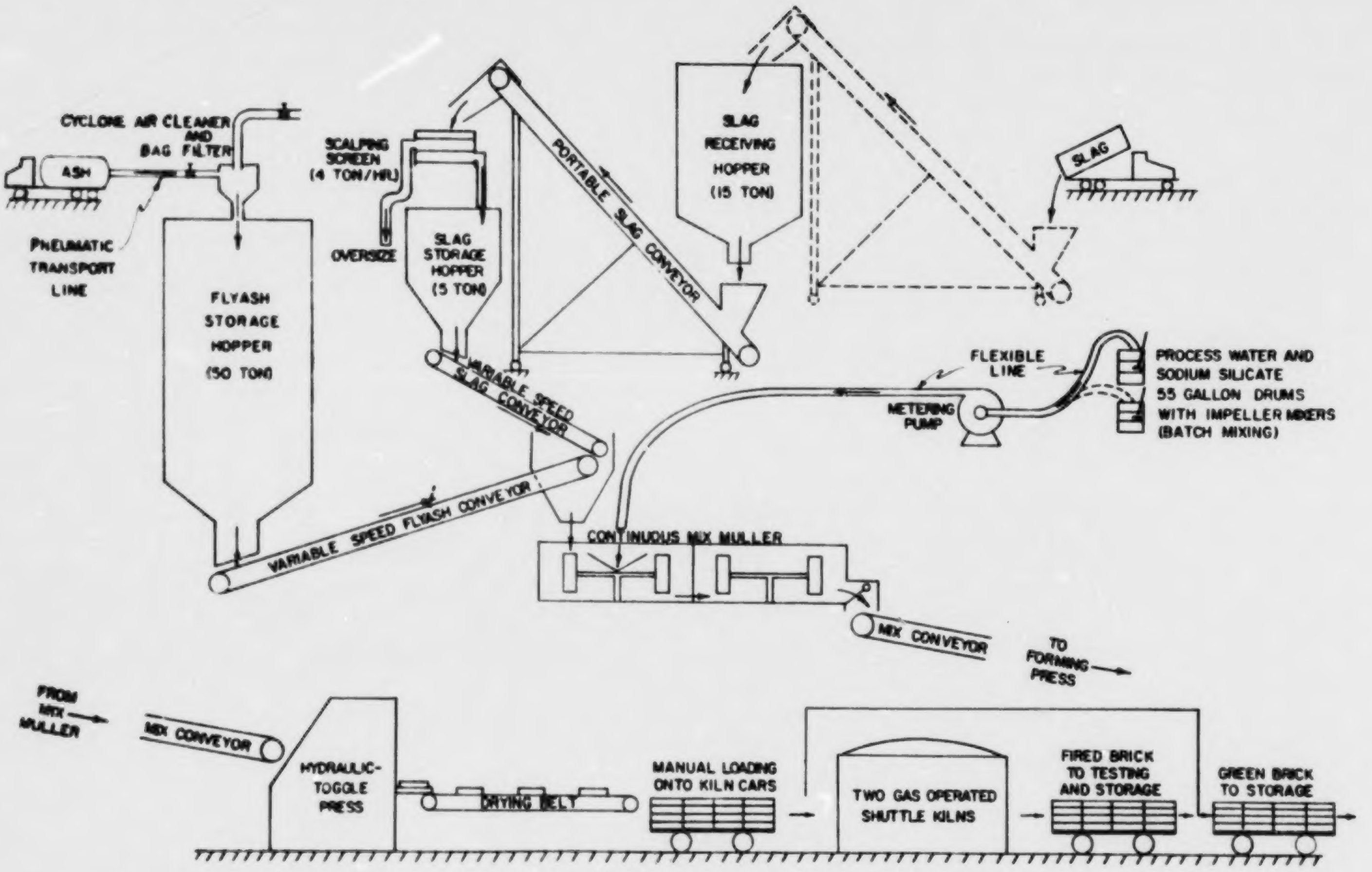
CYCLONE AIR CLEANER AND BAG FILTER
ASH
PNEUMATIC TRANSPORT LINE
FLYASH STORAGE HOPPER (50 TON)
SCALPING SCREEN (4 TON/HR)
OVERSIZE
SLAG STORAGE HOPPER (5 TON)
PORTABLE SLAG CONVEYOR
SLAG RECEIVING HOPPER (15 TON)
SLAG
VARIABLE SPEED SLAG CONVEYOR
VARIABLE SPEED FLYASH CONVEYOR
CONTINUOUS MIX MULLER
FLEXIBLE LINE
METERING PUMP
PROCESS WATER AND SODIUM SILICATE 55 GALLON DRUMS WITH IMPELLER MIXERS (BATCH MIXING)
MIX CONVEYOR
TO FORMING PRESS
FROM MIX MULLER
MIX CONVEYOR
HYDRAULIC-TOGGLE PRESS
DRYING BELT
MANUAL LOADING ONTO KILN CARS
TWO GAS OPERATED SHUTTLE KILNS
FIRED BRICK TO TESTING AND STORAGE
GREEN BRICK TO STORAGE

FIGURE 73. *Schematic flow diagram—continuous test plant OCR–WVU fly-ash based brick manufacturing process.*[77]

durability, workability, finish, chemical resistance, and volume change, are not well understood. Such unknowns in the applications of fly ash in concrete require considerable experience on the part of the designer. These limitations plus economic considerations have prohibited more wide-scale utilization of fly ash as a concrete constituent.

Soil stabilization. Pure lime has been used for purposes of soil stabilization in construction for centuries, but even the Romans noted that mixtures of lime and pozzolanic materials were superior to lime alone. Fly ash is used advantageously with lime today for soil stabilization in the construction of roads, parking areas, airport runways, embankments, and foundations. Interest in the use of lime fly-ash mixtures for these purposes dates back to the 1940's. Lime fly-ash stabilization as practiced today includes the use of lime fly-ash mixtures with both sized aggregates and soils. Since soil characteristics and properties vary greatly, the selection of stabilization agents, including fly ash, must be based upon tests and studies of the soil being treated.

Asphalt paving mixes. Fly ash has also been used to a limited degree as a fine mineral filler for asphalt paving mixes.

Primary factors determining the suitability of fly ash for this application are particle size and carbon content. This application is most often limited by the availability of other low-cost fillers such as limestone dust.

Soil conditioner. The U.S. Bureau of Mines is sponsoring research at Virginia Polytechnic Institute to investigate the use of fly ash as a soil conditioner and fertilizer. Fly ash contains elements essential to plant nutrition, and preliminary studies have indicated increased crop yield after fly ash addition. Basic chemical and physical reactions between soils and fly ash will be determined and evaluated in terms of crop yield.

Water and waste water treatment. Studies conducted by the Bureau of Mines indicate that fly ash may be an effective adsorbent for removing organic contaminants from secondary sewage treatment plant effluents.[73] A similar application relates to sludge dewatering.[74] Studies have indicated that coal fly ash facilitates sludge dewatering and thus might prove to be an effective filter aid.

Lightweight aggregate. Lightweight aggregates can be made by sintering coal fly ash. Sintering refers to the process of heating a loose material to a temperature at which it softens and agglomerates, but does not melt into a solid mass. Bulk densities attained through laboratory and pilot studies compared favorably with those of available lightweight aggregates manufactured from clay shale or blast furnace slag.

Fly-ash based bricks. Studies conducted by the Coal Research Bureau at West Virginia University (OCR–WVU) have indicated the possibility of producing dry-pressed fly-ash based brick without close controls on the physical and chemical properties of the ash.[75-77] Experiments have indicated that a fly-ash content of 74 percent combined with about 23 percent coarser aggregate and 3 percent sodium silicate binder, on a dry basis, yielded a suitable product. Tests indicate that the coarse aggregate can be eliminated if a fairly coarse fly ash is used resulting in a product containing about 97 percent coal fly ash. The fly-ash bricks have structural properties similar to clay bricks (Table 44). The Coal Research Bureau has suggested a configuration for a full-scale plant (Figure 73). An economic analysis has been made for two plant sizes, 3,000 and 9,000 bricks per hr (Table 45). Gross profits are based upon a selling price of $55 per thousand, a common price for clay brick. The percentage of fly ash upon which profits are based is not clearly defined in the analysis.

Economics. Except for the studies conducted by the Coal Research Bureau on the manufacture of bricks from fly ash, cost data for U.S. fly-ash products is not generally available. Presumably this is the result of the limited production of these materials in the United States. Cost data is available for fly-ash utilization plants in the Federal Republic of Germany (Table 46). Of particular interest is the relatively large plant capacity (in terms of fly-ash consumption) that appears to be required for economical operation.

TABLE 44

COMPARISON BETWEEN THE PHYSICAL PROPERTIES OF CLAY BASED BRICK AND FLY-ASH BASED BRICK [77]

ASTM standard specifications	ASTM grade NW clay brick	ASTM grade MW clay brick	ASTM grade SW clay brick	Fly-ash* based brick
Compressive breaking strength (psi).	1,500 min	2,500 min	3,000 min	3,000–20,000
Saturation coefficient	No limit	0.88 max	0.78 max	0.72–0.86
Water absorption (percent after 5-hr boil).	No limit	22.0 max	17.0 max	12–22

Other properties	Clay brick	Fly-ash brick
Apparent porosity (percent)	Probably less than fly-ash brick.	22–35.
Linear shrinkage on firing	Probably greater than fly-ash brick.	0–8.
Suction (gm H_2O/30 in.^{2}/min)		75–300.
Bulk density	Generally 130–160	90–120.
Color range	Whites to buffs to deep reds.	Same color range as clay brick.

*Properties vary within the indicated range depending on fly-ash, slag, sodium silicate, and manufacturing conditions used.

TABLE 45

ESTIMATED ECONOMICS OF PRODUCING FLY-ASH BASED BRICKS USING THE WVU-OCR* PROCESS

Capacity (bricks/hr)	Fly-ash consumption (tons/hr)	Capital cost ($)	Estimated gross profit ($/1000 brick)
3, 000	5	1, 074, 000	19. 23
9, 000	15	2, 293, 000	24. 48

*WVU-OCR: West Virginia University, Office of Coal Research.

TABLE 46

SPECIFIC CAPITAL COSTS OF COAL FLY-ASH UTILIZATION PLANTS IN THE FEDERAL REPUBLIC OF GERMANY [78]

Product	Production (cu yd/day)	Ash used (tons/day)	Capital cost ($/ton ash per day)
Cewilith (aggregate)	460	500	0. 10
Corson-Lite sinter	750	400	2. 20
Lime-bonded bricks	360	500	1. 25
Cellular concrete	460	180	9. 70

PROSPECTS FOR THE UTILIZATION OF REFUSE INCINERATOR FLY ASH

The utilization of fly ash from municipal refuse incinerators has not been practiced in the United States, and there has been only limited experience in this practice in Europe. However, fly ash and incinerator residues from a refuse incinerator in Berlin are recovered for sintering and the production of lightweight aggregate.

The extent to which incinerator fly ash can be employed in applications similar to coal fly ash has not been established. Presumably, the compositions of the two ashes are different since they result from burning entirely different materials. The long-range potential for fly-ash recovery does not appear to be great unless recovery is included in the salvage process for incinerator residues and ashes (discussed in a later section). The limited market for fly-ash products, the cost of producing a usable ash, and the large quantities that must be processed to render a plant economically sustaining are the main reasons for this low potential. It is possible, however, for the situation to change, especially if new and highly economical processes and products can be developed such as the CCR–WVU brick manufacturing process.

SALVAGE OF MUNICIPAL SOLID WASTE

TIN CANS

Tin cans are removed from municipal solid waste for salvage purposes at several localities throughout the United States. Tin cans are salvaged at several municipal incinerators and at nearly all compost plants. Until 1961, Los Angeles had separate collection and salvage of tin cans, which resulted in an income to the city of approximately $500,000/year. Municipalities do not sell salvaged cans directly, but rather deal through a scrap broker. Two brokers handle almost all the can salvage in the United States: Proler Steel Company, Houston, Texas, and Los Angeles By-Products Company, Los Angeles, California.

In addition, the Los Angeles By-Products Company salvages tin cans at landfills in the San Francisco area.

Utilization technology. Three potential uses of salvaged tin cans are known—as precipitation iron in a leaching process for the beneficiation of copper ore, as a source of tin through chemical detinning operations, and as a source of steel scrap for reuse in steelmaking. By far the largest use of salvaged cans today is for precipitation iron, since salvaged cans do not readily meet the high-quality scrap requirements in either the detinning or steelmaking processes. In addition, the use of recovered tin cans at copper mines is constrained by high shipping costs and limited demand. Nevertheless, the largest use of tin cans is in refining copper ore. Copper bearing ores encompass a diverse range of materials and require a wide range of techniques for beneficiation. For ores rich in oxides, a leaching process based on a copper-iron ion-exchange process is used, with detinned cans as a source of iron. Ore is dumped on large piles of tin cans and a 5 to 10 percent solution of sulfuric acid is percolated through the pile.

The ore reacts with the sulfuric acid, and copper sulfate is formed. When the copper sulfate reaches the tin cans, ferrous sulfate is formed and copper precipitates on the cans.[79,80] The precipitated copper (cement copper) is washed off, decanted, and sent to the smelting operation. Theoretically only 0.878 lb iron is required to precipitate 1 lb copper, but in practice this often reaches 2 lb iron per lb copper.

Incinerated and shredded tin cans having a bulk density of 20 to 25 lb per cu ft are an excellent source of precipitation iron because of their high surface-to-volume ratio.[79,81] Incineration is required to burn off trash and other contaminants, including tin. It has been reported, however, that the increasing aluminum content of cans causes problems in the precipitation process. In addition, the requirement for low bulk density materials increases shipping costs considerably. The cost of shipping shredded cans by rail from Washington, D.C., to copper mines in Arizona or Utah has been estimated at over $80 per ton. Since most copper mines can buy shredded cans for $50 to $65 per ton, with an upper limit of $75 per ton,[79,81] shipping cost is a critical factor. At the $75 limit, the feeling is that the copper companies would find it more economical to make sponge iron from slag or other material. Proler Steel Company has facilities at at least one copper mine for onsite shredding.[79]

Although the copper industry is the largest consumer of scrap tin cans, it does not constitute an infinite market, since less than 4 percent of the copper ore in the United States is refined by the leaching/cementation process.[80] In 1966, approximately 250,000 tons of tin cans were employed for this purpose. This constitutes only about 2.5 percent of all the cans available in municipal refuse. Furthermore, it has been estimated that the maximum potential consumption is only about 5 percent of the cans available in refuse.[79] Consequently, before truly large-scale reutilization of tin cans becomes a reality, another market must be developed. One potential market for tin cans is the detinning industry where tin from industrial tin-plate scrap is recovered.

The common industrial technique used for tin recovery is the alkaline chemical process.[82] Scrap is treated with a hot solution of caustic soda in the presence of an oxidizing agent, usually sodium nitrate or nitrite, and tin is dissolved as sodium stannate. The tin is then recovered from solution as sodium stannate crystals, as metal by electrolysis, or as tin oxide by neutralization of the solution with sulfuric acid or carbon dioxide. However, lacquer coatings on tin plate interfere with the detinning solution; fats, waxes, and greases also create problems. Thus, the potential use of salvaged tin cans hinges on the capability to get the cans clean. Once this is accomplished, there should be no reason why used tin cans cannot be an excellent source of tin-plate scrap. Even though the current supply of tin scrap is not great, detinners have not been motivated to increase the supply by cleaning cans. It has been estimated that 90 percent of the tin plate produced is lost through the disposal of tin cans.[79]

Steelmaking, especially in conjunction with tin recovery, is another potential use of tin cans. Since the detinning process does not affect the steel, detinned steel scrap is often used in steelmaking. The steel-scrap industry, however, is faced with many difficulties. Steel has been manufactured conventionally by processing iron ore in a blast furnace to produce pig iron. Pig iron is then further refined in the open hearth furnace to produce steel. Retention time in the open hearth is on the order of 6 to 8 hr. Recently the basic oxygen furnace, with processing times on the order of 15 min, has begun to replace the open hearth. Because of the short processing times, only a very limited amount of scrap can be tolerated in the basic oxygen furnace. Consequently, the market for scrap has decreased in recent years. This may be offset, however, by the advent of the electric furnace, which can produce steel from a charge of 100 percent scrap. This change will not occur overnight since a steelmaker is not likely to switch to electric furnaces until the supply of ore becomes short. In addition, the price of scrap is volatile compared to that of ore which is predictable, if not stable. The subtle details of the steel-scrap industry have been the subject of recent articles.[83,84]

There are other problems in recovering steel from tin cans. The tin and zinc content foul refractory linings in steel furnaces. However, tin-removal problems may be reduced somewhat during incineration. Studies conducted by the U.S. Bureau of Mines indicates that the tin content of cans ranges from 0.3 to 0.4 percent and that incineration will reduce this to 0.25 to 0.35 percent. A maximum of approximately 0.04 percent can be tolerated in steelmaking.[81] As previously indicated, a more economical process combination might be that of detinning followed by recovery for steelmaking. Both the technology and

TABLE 47

THIRTEEN MUNICIPAL INCINERATORS PRACTICING METAL SALVAGE IN 1968

Location	Plant	Year built	Type furnace	Capacity (tons/day)	Income from cans		Capital cost*	
					($/ton)	($ total)	Total ($)	Metal salvage equipment
Atlanta, Georgia	Mayson	1939 and 1952.¶	Rotary kiln	¶#700	#17.58	#150,000	¶2,050,000	
Atlanta, Georgia	Hartsfield	1963	Rotary kiln	¶#500	#17.58		#3,338,000	#200,000
Louisville, Kentucky		1957	Rotary kiln	#1,000	†#15.82			
Chicago, Illinois	Southwest	1963	Rotary kiln	#**1,200	#11.23		**6,825,000	
Chicago, Illinois	Stickney (private).	1958	Rotary kiln					
Chicago, Illinois	Boda (private).		Rotary kiln					
Chicago, Illinois	Medill	1956	Batch, rocking grate.	#780	#11.23			
Chicago, Illinois	Calumet	1959	Rotary kiln	#1,200	#11.23			
Broward County, Florida‡	No. 1	1964	Continuous reciprocating grate.	#150			#1,200,000	#40,000
Broward County, Florida‡	No. 2	1964	Continuous reciprocating grate.	#150			#1,200,000	#40,000
Tampa, Florida		1967	Rotary kiln					
Dayton, Ohio	Montgomery County.	1967	Rotary kiln					
DeKalb County, Georgia		1967	Rotary kiln					

Based upon: Day & Zimmermann, Engineers and Architects. Can-metal recovery. *In* Special Studies for Incinerators; for Government of the District of Columbia, Department of Sanitary Engineering. Public Health Service Publication No. 1748. Washington, U.S. Government Printing Office, 1968. p. 75–80. Except as noted in the last three items below.

*Not adjusted to 1968 conditions.

†Net profit of $7.40 per ton of cans has also been quoted.

‡Currently metal salvage not being practiced due to lack of market for product; no provision at these plants for washing or shredding of cans.

§Not completed at time of survey—planned metal salvage facilities.

¶Personal communication from D. Speer, Public Works Department, City of Atlanta, Georgia, to N. L. Drobny, April 22, 1968.

#Sullivan, M., U.S. Bureau of Mines, Department of Interior, College Park, Maryland.

**ASME Incinerator Committee, Midwest Section, Minutes of Meeting, June 3, 1966, Chicago, Illinois.

economies of using this combination on tin cans remains to be investigated.

Existing salvage operations. As indicated, most compost plants employ magnetic separation to salvage tin cans. In addition, tin cans are reported to be salvaged at 11 municipal and two private incinerators (Table 47).

Most incinerators sell their cans to Proler Steel Company at a price varying from $10 to $20 per ton. Indications are that most of the cans end up at copper mines in the West, although there is some indication that a small fraction is sent to South America.

A recent study examined the possibility of incorporating tin can salvage facilities at the proposed Incinerator No. 5 in the District of Columbia (Figure 74).[81] Estimated cost to include a can-metal recovery system in conjunction with the 800-ton-per-day incinerator was $400,000. It was calculated that the total cost of recovering can metal would be $13.60 per ton including operating and amortization charges. It was further estimated that shipping costs from Washington to copper mines in Utah or Arizona would be $83 per ton, and that the can-metal operation would therefore be impractical.

PAPER

This discussion is concerned with the recovery of wastepaper (or paper stock as it is termed in the industry) from municipal solid waste for reuse in the manufacture of paper-oriented products. The use of wastepaper in various chemical and biochemical conversion processes for the manufacture of entirely new by-products was discussed earlier.

In 1966, approximately 10 million tons of paper stock were recovered for reuse. This represented about 21 percent of the total fiber utilized in the manufacture of paper and paperboard products in the United States.

Although many grades of paper stock exist, three basic categories may be defined. The pulp substitute category includes bleached foodboard side runs and various other white cuttings which require very little preprocessing other than defibering. The deinking category primarily includes heavy books and ledgers. The use of magazines, once a major deinking item, has declined due to the increasing amounts of adhesives, fillers, and other contaminants, which make deinking uneconomical with existing technology. A new, more economical process for deinking clean salvaged newsprint has been developed by Garden State Paper Company of Garfield, New Jersey.[85-87] Deinking grades constitute only about 15 to 20 percent of the total paper stock utilization in the United States.[88] The third major category of paper stock, and one which accounts for 70 percent of the paper stock consumed, is bulk grade.[89] This category consists mostly of mixed news and corrugated, and is used principally in the manufacture of fiberboard containers and boxboard, molded pulp products such as egg cartons and flower pots, and felt roofing

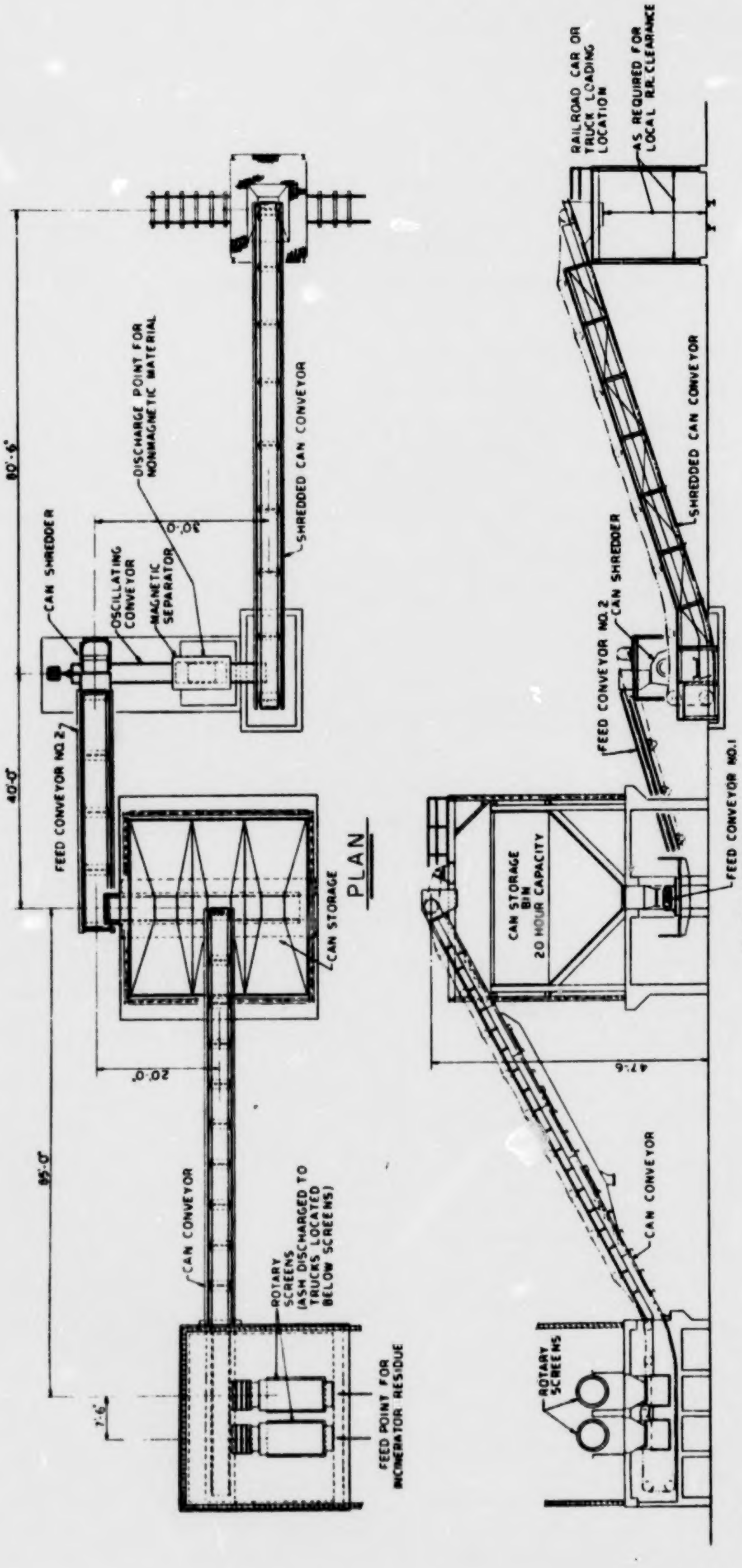
PLAN
ELEVATION
CAN SHREDDER
OSCILLATING CONVEYOR
MAGNETIC SEPARATOR
DISCHARGE POINT FOR NONMAGNETIC MATERIAL
SHREDDED CAN CONVEYOR
FEED CONVEYOR NO.2
CAN STORAGE
CAN CONVEYOR
ROTARY SCREENS (ASH DISCHARGED TO TRUCKS LOCATED BELOW SCREENS)
FEED POINT FOR INCINERATOR RESIDUE
80'-6"
40'-0"
95'-0"
7'-6"
30'-0"
20'-0"
RAILROAD CAR OR TRUCK LOADING LOCATION
AS REQUIRED FOR LOCAL R.R. CLEARANCE
CAN STORAGE BIN 20 HOUR CAPACITY
FEED CONVEYOR NO.1
47'-6"
ROTARY SCREENS

FIGURE 74. *Can-metal recovery system investigated for Incinerator No. 5, District of Columbia.*[91]

materials and building board.

Recent market prices for paper stock vary from $8 to $16 per ton depending on the grade (Table 48). The motivation for paper stock recovery is economics. Recovery is practiced only when manufacturing costs using paper stock are lower than those using virgin pulp. Prices are by no means stable and vary both geographically and temporally. The relatively low market prices reflect both the difficulties and costs associated with the use of paper stock as a raw material and the readily available supply of virgin pulpwood at moderately low cost.

Recovery of paper stock from municipal solid waste. As recovery of the high quality material required for even bulk grades of paper stock is not economical, the major potential for the recovery of paper stock from municipal solid waste lies in salvaging clean newsprint and corrugated. The other major forms of paper in mixed refuse are magazines and packaging materials. As indicated, the recovery of magazines is becoming less attractive economically, because of the increase in the amounts of inks, lacquers, and adhesives used. The situation with packaging materials is similar; generally, the function of these materials dictates that considerable quantities of coating and other protective materials be employed. In addition, packaging materials are often contaminated by the product they contained, which interferes with fiber recovery.

The National Committee for Paper Stock Conservation is interested in promoting the recovery of newsprint and cardboard from solid waste, but emphasize that only high quality material can be tolerated in the recovery process, and that responsibility for providing high quality material rests with the supplier. The committee further believes that household separation of newsprint and cardboard from other wastepapers is essential to insure the supply of contaminant-free material.[92]

Recovery of paper stock from municipal refuse is currently practiced to a small extent. As previously indicated, most compost plants remove clean newsprint and corrugated by hand at the plant both for salvage and to upgrade the quality of the compost produced. Approximately ½ to ¾ tons per hr can be handsorted by one man, corresponding to 1.3 to 2 man-hr per ton or a separation cost on the order of $3.50 to $5 per ton, assuming very low-cost labor. These plants sell the paper stock on the open market

TABLE 48

SELECTED SECONDARY FIBER USAGE, PAPER STOCK GRADES, SPECIFICATIONS, AND RECENT MARKET PRICES [90,91]

Grade description and specifications *,[90]	Market price Jan. 20, 1967 [91] ($/ton)	
No. 2—Mixed paper:	*Percent*	
Consists of a mixture of various qualities of paper not limited as to type of packing or soft stock content		
Prohibitive materials may not exceed	2	----------------
Total outthrows may not exceed	10	----------------
No. 1—Mixed paper		
Consists of a mixture of various qualities of paper, packed in bales weighing not less than 500 lb and containing less than 25 percent of soft stocks such as news		
Prohibitive materials may not exceed	1	$8.00–$9.00 (New York)
Total outthrows may not exceed	5	----------------
Super mixed paper		
Consists of a clean sorted mixture of various qualities of papers, packed in machine-compressed bales not less than 60 in. in length and containing less than 10 percent of soft stocks such as newspapers		
Prohibitive materials may not exceed	0.5	$11.00–$13.00 (Chicago)
Total outthrows may not exceed	3	----------------
Boxboard cuttings		
Consists of baled new cuttings of paperboard such as are used in the manufacture of folding paper cartons, setup boxes and similar boxboard products		
Prohibitive materials may not exceed	0.5	----------------
Total outthrows may not exceed	2	----------------
No. 1—News:		
Consists of newspapers packed in bales of not less than 54 in. in length, containing less than 5 percent of other papers		
Prohibitive materials may not exceed	0.5	$15.00–$16.00 (New York)
Total outthrows may not exceed	2	
Super news:		
Consists of sorted fresh newspapers, not sunburned, packed in bales of not less than 60 in. in length, free from papers other than news, and containing not more than the normal percentage of rotogravure and colored sections		
Prohibitive materials None permitted		
Total outthrows may not exceed	2	$18.00–$20.00
Over-issue news:		
Consists of unused overrun regular newspapers printed on newsprint, baled or securely tied in bundles, and shall contain not more than the normal percentage of rotogravure and colored sections		
Prohibitive materials None permitted		$22.00–$23.00 (New York)
Corrugated containers:		
Consists of corrugated containers having liners of either jute or kraft, packed in bales of not less than 54 in. in length		
Prohibitive materials may not exceed	1	$16.00–$18.00 (New York)
Total outthrows may not exceed	5	

*Grade definitions: The definitions described are intended to define grades as they should be packed and graded. Consideration should be given to the fact that paper stock, as such, is a secondary material produced manually and may not be technically perfect.

Outthrows: The term "outthrows" as used throughout this section is defined as "all papers that are so manufactured or treated or are in such a form as to be unsuitable for consumption as the grade specified." The maximum quantity of "outthrows" indicated in connection with the above grade definitions is understood to be the total of "outthrows" and "prohibitive materials."

Prohibitive materials: The term "prohibitive materials" is defined as

(1) any material which by their presence in a packing of paper stock, in excess of the amount allowed, will make the packing unusable as the grade specified

(2) any materials that may be damaging to equipment.

to various brokers for unspecified end-uses, although most of it would be expected to be used in processing various bulk grades of paper. If paper stock recovered from municipal solid waste is classified in the bulk category, the maximum potential market for these materials may be estimated. The bulk category accounts for 70 percent of total secondary fiber usage or about 7 million tons per year. If 22 percent of typical municipal solid waste is newsprint and corrugated, the total potential supply is about 35 million tons per year, about five times existing national demand. Widespread recovery for bulk paper stock has limited potential.

Processing systems. Deinking: The technology of deinking is well documented and has been described recently by the Technical Association of the Pulp and Paper Industry (TAPPI).[83] The description will not be repeated here since deinking technology is confined, for the most part, to higher quality paper stock than that which can be salvaged from solid waste.

The development of a satisfactory deinking process for the recovery of paper stock in mixed refuse, especially newsprint, could pave the way to large-scale recovery and utilization of this major form of paper stock from municipal solid waste. A recent study of conventional deinking practices has indicated that, while deinked stock can aid in economic and quality production, rising contaminant content is a major problem.[84] As previously indicated, the Garden State Paper Company, Garfield, New Jersey, has made significant contributions in the deinking of newsprints. Although details of this process are proprietary, basically they manufacture high quality newsprint from a supply of 100 percent salvaged newsprint, which includes a substantial fraction of overissue news. The quality requirements are high and can be satisfied only with presorted newsprint (i.e., newsprint which has not been soiled with mixed refuse). The success of Garden State's process has resulted in new plants now under construction in Pomona, California, and Alsip, Illinois.

Bulk fiber recovery: Black Clawson Company, Middletown, Ohio, has been active in the development of pulping systems for the recovery of mixed paper stock for use as bulk secondary fiber. A Black Clawson system installed in England has been described as processing 80 percent mixed waste and 20 percent container waste, packaging, etc. (Figure 75).[85] Daily throughput is about 200 long tons per day with rejects accounting for about 5,800 lb per day. At normal running conditions, the pulper requires 350 hp, but 500 hp is required to overcome starting torque. Efforts to obtain more information on this and similar systems were unsuccessful.

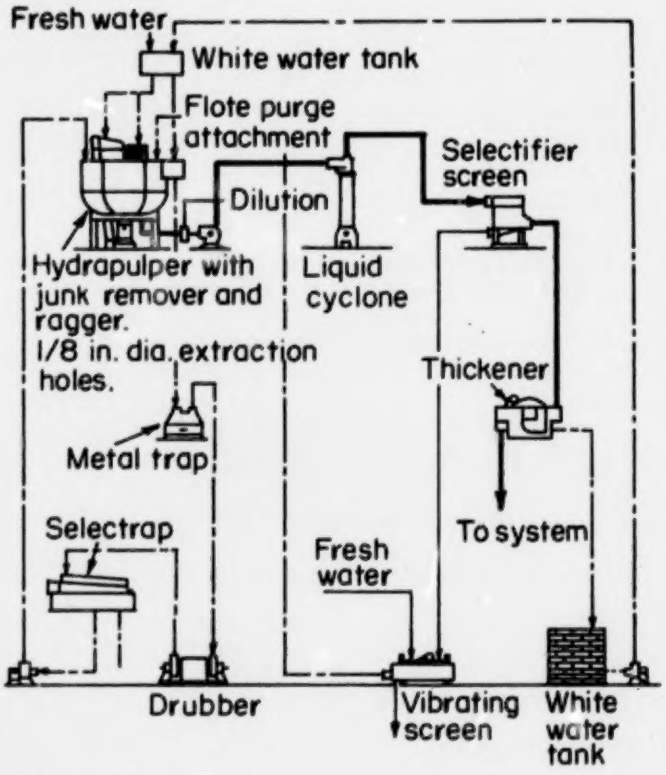

FIGURE 75. *Black Clawson fiber recovery system.*[85]

GLASS

The percentage of glass in municipal solid waste has grown significantly in recent years, primarily because of the advent of the nonreturnable bottle.[86]

Average returnable bottle life 10 yr ago was 35 to 40 round trips; today it is as low as eight. Nonreturnable bottles, of course, make only one trip. The waste problem is further compounded by the fact that many retailers prefer to discard returnable bottles rather than handle them for only a $0.01 to $0.02 refund.

The recovery of glass from municipal solid waste is limited due to both technical and economic considerations. Technical aspects of separating glass from compost have been mentioned in earlier discussions of the Osborne separator and the Sutton, Steele, and Steele stoners. Another potential technique, especially for segregating various colors of glass, is the Sortex optical sorter.

There are two major categories of salvaged scrap glass (properly referred to as cullet in the industry)—bottle glass, and sheet and plate glass. The type of glass cullet for which the major market exists is sheet and plate glass trimmings produced in various industrial operations including the manufacture of window sashes, doors, and automobile plate. This material is used to manufacture powdered glass which has a variety of industrial applications including reflective highway paints, abrasives, match heads and strikers, ammunition, refractory materials, and for the cleaning and tumbling of castings. Industrial sheet and plate cullet is ideally suited for these applications since it requires only minimal cleaning and fine grinding to use.

The major form of glass in municipal solid waste is bottles, and the market for bottle cullet is diminishing. Thirty to forty years ago, almost all of the glass cullet marketed was bottle cullet used to remanufacture bottles. Bottle cullet melts faster than raw materials; thus, older furnaces can be operated at greater capacity. The importance of this, however, has declined owing to increased costs (largely labor) of cleaning and processing bottle cullet; low-cost raw materials; and new glassmaking systems, which have accelerated processing.

A glass cullet dealer in Cleveland, Ohio, indicated that the only form of bottle cullet for which a Cleveland market exists is the discarded broken and defective bottles from bottling plants.[97] Market prices generally prohibit consideraticns of glass salvage from municipal refuse. In Cleveland, the maximum price brokers will pay for cullet is about $5 to $6 per ton. Prices received for crushed and cleaned cullet is proprietary information. Existing markets for such cullet are decreasing and will continue to shrink; the market is mostly composed of manufacturers with older equipment that needs the fast melting rates of cullet.

There is no technical reason why bottle cullet cannot be used in the manufacture of powdered glass, which is the major market for glass cullet. The problem, however, is the abundant supply of scrap plate and sheet glass which exceeds the demand for cullet for this purpose.

Another use identified for glass cullet salvaged from municipal solid waste is in the manufacture of foam glass. A Polish process is claimed to manufacture foam glass from 100 percent unsorted waste cullet.[98] Although no data on product characteristics or production costs are provided, the potential is extremely limited because the overall growth potential of the foam glass market is not significant.

PLASTICS

Plastics constitute only about 1 percent of typical mixed refuse. Studies conducted by Battelle have indicated that the percentage composition should increase to slightly over 3 percent by 1976, for a total of about 11 billion lb of plastic waste annually.[99] This three-fold increase is attributed almost entirely to expected increases in the use of convenient packaging materials, which are expected to constitute about 6,600 million lb by 1976 (Table 49).

Generally speaking, plastics are one of two types—thermoplastic and thermosetting. Thermoplastic materials are readily recovered by remelting and this is often done within a manufacturing facility. Thermosetting materials, on the other hand, cannot be reworked. Thermoset plastics are composed of cross-linked networks with the molecular chains bonded to one another where they cross. The strength of these bonds makes the thermosetting materials more resistant to heat and chemical solvents and causes them to retain their shape until decomposition temperature is reached. Major types of thermoplastics in solid waste have been estimated by Battelle as follows [99]: polyethylene (38%), polyvinylchloride (32%), and polystyrene (21%).

The recovery of plastics from solid waste is complicated by manufacturing requirements for high quality scrap, which is expensive. Virgin raw materials are readily available at costs ranging from $0.10 to $0.20 per lb. This leaves very little margin for salvage and separation costs; clean and baled plastic milk bottles, for example, bring only $0.03 to $0.04 per lb. Another problem, again related to quality considerations, is the predominance of plastic laminates containing both thermoplastic and thermosetting plastics, whose molecular structures are incompatible. Fabrication of products from scrap containing mixtures of these materials is impossible. In addition, several constraints exist with regard to potential uses of plastics. For example, regulations prohibit the reuse of plastic waste material in the packaging of food products.

There are also many technical problems in separating plastics from mixed refuse. The first attempt in this country to separate film plastics from mixed refuse is at the Gainesville compost plant in Florida, where a ballistic type separator was used experimentally in conjunction with an air stream that functioned as a giant vacuum cleaner. The plastic film was not separated for salvage, but to upgrade the compost and to reduce blowing film plastic, a problem at most compost plants. At present, the salvage of plastic from mixed refuse does not have much promise. No techniques exist for processing mixed plastic in the manufacture of new products, although it has been suggested that short-chain polymers might be recovered from thermosetting plastics by pyrolytic distillation.[100]

RUBBER

In the salvage and recovery of rubber are found two factors not associated with the recovery of other solid waste materials: (1) a practical method exists for recovery, and (2) scrap quality (mixes of natural and synthetic rubber) is not a severe constraint. The availability of reclaimed rubber for use in the rubber goods industry has been instrumental in minimizing excessive and sustained rises in the cost of crude rubber.[100] Reclaimed rubber also has technological advantages over synthetic and crude rubber. It can be mechanically masticated more rapidly than most synthetic or crude rubber and is well adapted to the absorption of fillers.

TABLE 49

ESTIMATES OF PLASTICS USE IN PACKAGING IN 1966 AND 1976[99]

Components	Amount (millions of lb)	
	1966	1976
Plastic bottles	900	1, 800
Other rigid plastic containers (closures, flexible tubes, etc.)	1, 000	1, 500
Plastic film and sheet	1, 600	2, 300
Plastic coatings and adhesives	750	1, 000
	4, 250	6, 600

In addition to the recycle of reclaimed rubber in the rubber industry, some promising experimental work has been done with the pyrolysis of scrap automobile tires to produce carbon.[101]

The rubber content of mixed municipal solid waste is considered to be very low (0.5 to 1.5%) although no extensive studies have been conducted to establish composition ranges. Domestic rubber waste consists of items such as hot water bottles, shoes, rainwear, and the variety of other household items that contain rubber pads, gaskets, washers, and occasionally rubber tires.

Rubber tires, most frequently disposed of in service stations, constitute the major source of scrap rubber, accounting for 16 percent (360,000 tons) of the total U.S. rubber usage in 1962.[102] About 60 percent of the reprocessed rubber is used in the manufacture of new tires. Other uses include the manufacture of automobile floor mats, windshield mounting strips, rubber hose, rubber inner soles, heels, and motor mounts.

The price of salvage rubber varies with demand and locale. A processor in St. Louis, a high demand area, is reported to pay $14 per ton delivered,

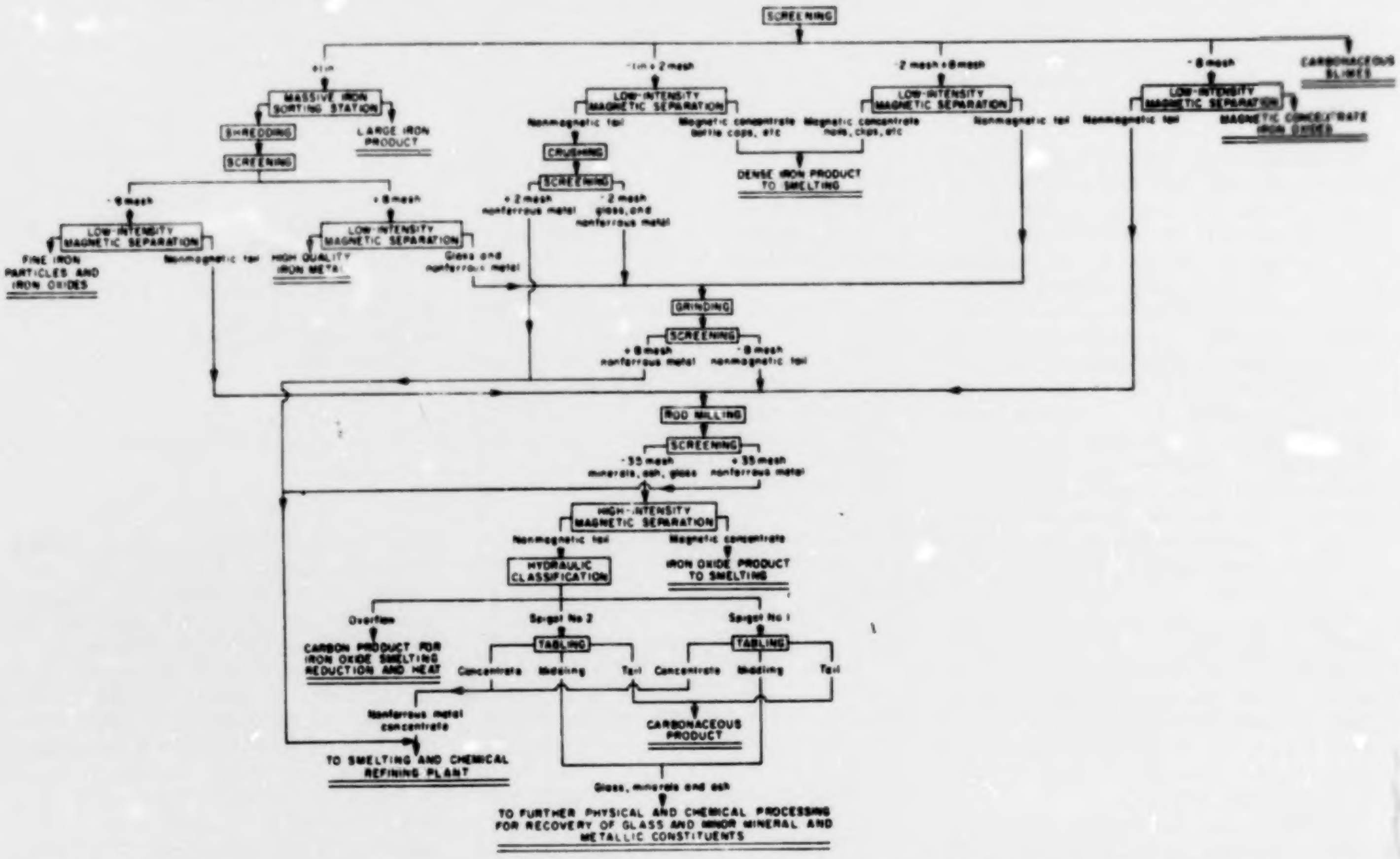
SCREENING
+1 in
-1 in +2 mesh
-2 mesh +8 mesh
-8 mesh
CARBONACEOUS SLIMES
MASSIVE IRON SORTING STATION
LARGE IRON PRODUCT
SHREDDING
SCREENING
-8 mesh
+8 mesh
LOW-INTENSITY MAGNETIC SEPARATION
FINE IRON PARTICLES AND IRON OXIDES
Nonmagnetic tail
HIGH QUALITY IRON METAL
Glass and nonferrous metal
Nonmagnetic tail
Magnetic concentrate bottle caps, etc
Magnetic concentrate nails, clips, etc
DENSE IRON PRODUCT TO SMELTING
Nonmagnetic tail
Nonmagnetic tail
MAGNETIC CONCENTRATE IRON OXIDES
CRUSHING
SCREENING
+2 mesh nonferrous metal
-2 mesh glass, and nonferrous metal
GRINDING
SCREENING
+8 mesh nonferrous metal
-8 mesh nonmagnetic tail
ROD MILLING
SCREENING
-35 mesh minerals, ash, glass
+35 mesh nonferrous metal
HIGH-INTENSITY MAGNETIC SEPARATION
Nonmagnetic tail
Magnetic concentrate
HYDRAULIC CLASSIFICATION
IRON OXIDE PRODUCT TO SMELTING
Overflow
Spigot No 2
Spigot No 1
CARBON PRODUCT FOR IRON OXIDE SMELTING REDUCTION AND HEAT
TABLING
Concentrate
Middling
Tail
TABLING
Concentrate
Middling
Tail
Nonferrous metal concentrate
CARBONACEOUS PRODUCT
TO SMELTING AND CHEMICAL REFINING PLANT
Glass, minerals and ash
TO FURTHER PHYSICAL AND CHEMICAL PROCESSING FOR RECOVERY OF GLASS AND MINOR MINERAL AND METALLIC CONSTITUENTS

FIGURE 76. *Bureau of Mines experimental procedure for physical beneficiation of metal and mineral values in incinerator residues.*[106]

whereas, in Los Angeles, a low-demand area, the market price is only about $7.50 per ton delivered.[102]

RAGS

Rags are salvaged by industrial brokers for use in the manufacture of fine writing paper and roofing paper. In general, the removal or separation of rags from mixed solid waste is not practical because of the presence of contaminants and the difficulty of discriminating between natural and synthetic fibers. Synthetic fibers cannot be used by the paper industry, and so the salvage of rags from municipal solid waste is generally uneconomical. Nevertheless, two compost plants have reportedly elected to salvage clean rags when the market price reaches $40 per ton.[103, 104] Handsorting is expensive, but is the only means of obtaining a satisfactory clean product. Salvage is further compounded by relative scarcity of brokers interested in dealing in this rather marginal product.

INCINERATOR RESIDUES

As mentioned earlier, the Bureau of Mines is conducting extensive studies on the salvage of incinerator residues.[39, 105, 106] Analytical studies of residues from both rotary-kiln and grate-type furnaces have been made (Tables 50 and 51). Differences in the composition are attributed to the higher temperatures and, hence, greater burn-out achievable in rotary-kiln furnaces. Similar studies are being sponsored by the Bureau of Solid Waste Management at Drexel Institute of Technology, but data are not available at this writing.

The Bureau of Mines studies are being extended to apply existing minerals-beneficiation technology for the separation of various components (Figure 76). These studies, however, have been initiated only recently; and meaningful data are not yet available.

FINDINGS

SALVAGE VERSUS BY-PRODUCT RECOVERY

It is evident from the foregoing discussion that the outlook for the salvage of components in solid waste, except perhaps for tin cans, is much more limited than is the outlook for by-product recovery. There are two reasons for this. One is the relatively adequate supply and the corresponding low cost of most virgin materials that the salvaged components would replace or conserve. The second is the high quality demanded for recycle into manufacturing operations and the lack of separation technology for achieving this quality.

Even the recovery of tin cans on a large scale seems unattractive unless methods can be developed for cleaning the cans and producing a scrap which can be reused in steelmaking. As indicated previously, the present largest consumer of salvaged tin cans, the copper industry, has a limited potential demand.

By far the largest single component in solid waste is paper, but salvaging paper from mixed refuse presents even more serious problems. Other than handsorting, a separation technique is not available that compares to the efficiency of magnetic separation for tin can recovery. Technical problems prevent cleaning and deinking of pulp at an economical cost. As discussed earlier, the salvage of minor components such as glass, plastic, and rubber is also difficult.

Thus, the greatest economic potential for the future large-scale recovery and utilization of municipal solid waste lies in the manufacture of by-products. The reasons for this are: the small probability of developing new separation technology capable of extracting salvageable (high quality) materials; and the undersirable consequences associated with household separation. It is emphasized that this is true only in sense of classical engineering economics. It is quite possible that considerations related to external diseconomies (such as resource depletion) and social costs (such as pollution of the environment) might provide strong motivation for turning from conventional disposal-oriented to recovery-oriented methods of solid waste management.

DATA GAPS

Several needs may be defined for additional information and future research on salvage and by-product recovery. Salvage techniques need to be explored for the detinning and cleaning of tin cans so that they can be reused in the steelmaking process. Both chemical and thermal detinning possibilities should be explored.

In the area of by-product recovery, which appears to hold the largest potential for solid waste recovery, a general need is for new by-products and new uses. It can be seen that, although a large number of potential combinations and permutations of present equipment and processes exist, there are only a few basic recovery schemes and the number of potential by-products is limited. In addition to this rather general need, several specific needs related to process cost and performance data can also be defined.

With respect to composting, either new markets must be developed or processing costs must be decreased by process modifications, thereby improving the market situation of compost. One possible application which needs to be explored is the large-scale recovery of desert lands and abandoned mines. In order to close cost data gaps for existing composting systems, it seems essential that the true cost be established for manufacturing compost from solid waste. The wide range of cost estimates quoted in this report indicates the lack of agreement on this matter. If these costs can be established, allowing for adjustment due to differences in local markets, so that cities can evaluate the financial viability of a proposed composting contract, then the merits of this technique as compared to another alternative can be assessed. City officials do not have satisfactory guidelines at present for evaluating a proposed contract; and this information must be developed to prevent uneconomical attempts at solid waste recovery.

With regard to process modifications in composting, a significant decrease in processing time, and hence, cost might be possible using aerobic digestion of pulped solid waste in an aqueous slurry. Such a system would provide for more efficient oxygen-food-organism contact and would provide a greater reservoir of dissolved oxygen to guard against the development of local (and overall) anaerobic conditions.

For waste-heat recovery, available data on steam-production efficiency, optimum excess-air requirements, and optimum refuse: auxiliary fuel ratio must be investigated. Sensitivity to ranges in characteristics and composition of solid waste and their effect on the overall economies of waste-heat recovery must be determined. This needs to be done both for water-wall and waste-heat boiler systems. These studies then need to be expanded to a refined analysis of the economies of waste-heat recovery considering potential savings in terms of air pollution control equipment. In turn, this will require the development of sound cost-allocation procedures for determining the true incremental cost of waste-heat recovery and, hence, associated net savings.

In the related area of power production using refuse-fired turbines, the concept needs to be evaluated in light of previous unsuccessful experiments to use solid fuels in gas turbines. Because of the high research costs associated with the development of these systems, the potentials for success need to be established, and the assumptions upon which expected performance are based need to be reviewed in detail.

The utilization of and possible recovery techniques for incinerator fly ash and residues should be explored in investigations such as those being conducted for coal fly-ash utilization. For example, the manufacture of bricks and other structural shapes in a process similar to the one developed at West Virginia University for coal fly-ash utilization needs to be explored. This will, in all likelihood, require experimental studies to determine the effect of refuse ash characteristics and

TABLE 50

COMPOSITION OF GRATE-TYPE INCINERATOR RESIDUES [106]

Component	Average percentage*
Glass	44.1
Tin cans	17.2
Mill scale and small iron	6.8
Iron wire	0.7
Massive iron	3.5
Nonferrous metals	1.4
Stone and bricks	1.3
Ceramics	0.9
Unburned paper and chemical	8.3
Partially burned organics	0.7
Ash	15.4
Total	100.3

*Dry weight basis.

TABLE 51

COMPOSITION OF ROTARY-KILN INCINERATOR RESIDUES [106]

Component	Average percentage*
Fines, minus 8-mesh (ash, slag, glass)†	35.8
Glass and slag, plus 8-mesh‡	21.2
Shredded tin cans	19.3
Mill scale and small iron	10.7
Nonmetallics from shredded tin cans	6.5
Charcoal	3.4
Massive iron	1.9
Iron wire	0.5
Ceramics	0.2
Handpicked nonferrous metals	0.1
Total	99.6

* Dry weight basis.

† Of the total weight of this fraction, 1.8 percent is recoverable nonferrous metal.

‡ Of the total weight of this fraction, 1.4 percent is recoverable nonferrous metal.

composition on processing and to determine related economies. In addition, techniques should be explored and economies established as a basis of encouragement for municipalities to use the structural and soil conditioner properties of incinerator ash in municipal construction and land improvement projects.

SYNERGISTIC AND ANTAGONISTIC EFFECTS

The synthesis of new process combinations for solid waste recovery requires that the interactions among the available size reduction, separation, and recovery techniques be optimized as nearly as possible. This, in turn, requires a delineation of potential synergistic and antagonistic effects between the various unit processes. Relationships between the various size-reduction and separation processes have been discussed previously. Interactions between size-reduction and separation processes and the salvage and by-product recovery systems are discussed below.

The major potential for salvage from mixed solid waste is tin can recovery for steel scrap and to a limited extent for use by the copper industry. For efficient recovery of tin cans, some degree of size reduction is essential to free the cans as much as possible from entrapped and attached materials. Magnetic separation is indicated for separation; burnout and cleaning is also likely to be required. When waste incineration is to be provided at some point within the system, it may be desirable to defer magnetic separation until after incineration. This would provide a burnout of attached and entrapped material and a limited degree of detinning, perhaps eliminating an additional cleaning process.

In the area of by-product recovery and specifically compost production, several potentially unexplored synergistic effects exist. These basically relate to the potential advantages of producing compost in an aqueous slurry as opposed to the conventional mulch form. Conventional chemical engineering technology suggests that significantly increased mass transfer rates and, hence, reduced digestion time might be possible in an aqueous slurry system. In addition, it appears that the smaller particle sizes achievable in a wet pulping system would contribute significantly to increased mass transfer in an aqueous environment. Wet processing also opens other avenues of opportunities in that it may be possible to separate the organic biodegradable materials from the remaining noncompostables by flotation techniques prior to digestion.

Compost production is an excellent example of a by-product recovery process in which salvage may hold considerable merit, since high-quality compost can only be produced after the removal of impurities such as ferrous and nonferrous metals, glass, and plastic. Ferrous materials are conventionally and properly removed by magnetic separation. Nonferrous materials can be removed, in principle, either before or after biological digestion by a wet process such as flotation or by a dry process such as the stoners. In a slurry composting process, wet separation would most likely be indicated to avoid the need for drying and size reduction beyond the degree required for the final product.

With respect to incineration and waste-heat recovery, some degree of size reduction may be desirable to achieve increased burning rates. However, a lower size limit would exist below which fly-ash control and air-resistance problems would become excessive. Another critical factor is the economic trade-offs related to increased cost of producing smaller particle sizes versus the undefined economic advantages of increased performance of the incineration process. In addition to considering waste-heat recovery for potential sale, incineration may be considered in combination with one of the other recovery processes requiring drying of a product such as compost or protein.

In the area of chemical recovery, antagonistic and synergistic phenomena have not yet been identified because the processes are still under development. An exception perhaps exists in the area of pyrolysis, wherein it has been reported that an optimal particle size may exist. A rather general and perhaps obvious consideration is the selection of wet versus dry processing. Pyrolysis should be preceded only by dry-size-reduction and separation processes whereas hydrolysis, basically a wet process, could be preceeded by wet size reduction and separation.

At present, specific antagonistic and synergistic effects cannot be defined in the area of fly-ash recovery, although certain phenomena might be described. Once desirable fly-ash properties have been determined for various end uses, however, the variation of the critical factors as a function of feed composition, operating schedule, an incinerator design can be tested experimentally. At that time, potentially antagonistic and synergistic effects may be explored, and this may provide a means for product quality control.

VII. Conclusions

UNIT PROCESSES AND RELATED COST AND PERFORMANCE DATA

RELIABLE AND MEANINGFUL cost and performance data on unit processes for the recovery and utilization of mixed municipal solid waste are not generally available from existing operations owing to: the limited application of many equipment designs and processing techniques, the failure to collect meaningful data on the applications that do exist, and the proprietary nature of much of the available cost and performance data.

The only way for the Bureau of Solid Waste Management to obtain reliable and meaningful data on unit processes for the recovery and utilization of solid waste is to sponsor experimental studies and full-scale operations and to collect basic data in conjunction with such studies. Consequently, opportunities should be exercised at all existing solid wastes demonstration projects to collect cost and performance data on the various unit processes employed, and to experiment with other equipment types not originally provided in the plant designs. Uniform cost-allocation standards and procedures should be developed so that data collected from various installations can be compared.

The analytical design of size-reduction and separation equipment for processing industrial materials is generally not possible due to the nonhomogeneity of materials processed. Consequently, empirical studies are usually required to select equipment and operating conditions. The nonhomogeneity of solid waste dictates a need for even greater reliance on experimental studies; extrapolation of cost and performance data collected for selected industrial applications cannot be expected to yield reliable information for the design or evaluation of solid waste processing systems.

Although several wet and dry size-reduction equipment designs are suitable for processing solid waste for separation and recovery, the most versatile, in terms of material and particle size capability, is the hammermill. For processing waste streams not containing bulky materials, the rasp mill and drum pulverizer offer advantages. For high degree of size reduction (from very large to very small particles), a series of two or more stages of size reduction is more efficient than a single stage.

Except for handsorting and magnetic separation of tin cans and other ferrous materials, performance characteristics and associated costs for solid waste separation techniques are not well established.

BY-PRODUCT RECOVERY VERSUS SALVAGE

In the area of recovery and utilization of mixed solid waste, by-product recovery appears to have significantly greater economic potential in the classical sense than does salvage and should be given priority for research and development. There are three reasons for this: (1) The immediate and long-range market potential for the salvage of materials from solid waste appears to be unpromising, except perhaps for tin cans. The preliminary indications uncovered in this study, however, need to be explored in greater detail before a firm judgment can be made. (2) The high quality requirements for salvaged materials for reuse in manufacturing processes are beyond the economic and technical capabilities of existing and foreseeable separation technology. (3) By-product recovery systems do not require a high degree of feed preparation, and it is anticipated that processing requirements can, for the most part, be met by reasonably foreseeable extensions of existing separation technology.

The primary role of salvage in solid waste recovery should be an adjunct to a by-product recovery system if, for example, it is desirable to extract a given material in conjunction with manufacture or upgrading of a given by-product. For reasons outlined above, salvage should not be made the primary function of a mixed solid waste processing and recovery system.

Technically, the most promising technique for increasing the overall salvage potential of solid waste is household separation of clean newsprint and other paper, by far the largest single component in solid waste. Recovered paper has a definite market, and the long-range reuse and salvage potential is attractive, if a steady supply of clean materials can be guaranteed. It is likely, however, that advantages attributable to household separation will not be sufficient to justify disadvantages related to attempts to secure the public's cooperation. This is true because cellulose is not a critical resource; that is, modern forest management practices are capable of adequate replacement so that acute shortages of cellulose are not likely to develop.

ECONOMICS OF SOLID WASTE RECOVERY AND UTILIZATION

Throughout this report reference has been made to the economics of solid waste recovery. Based upon the information collected and the general trends observed during this study (and despite the fact that recovery of specialty items from municipal solid waste and the manufacture of specific products may prove to be economic for certain geographic areas or certain situations), it is concluded that the recovery and utilization of municipal solid waste may never become generally economic in the classical sense. This is because transportation and processing costs are likely to be so high that products recovered or manufactured from solid waste will cost more than their conventionally manufactured counterpart or, alternatively, the process must operate at a loss to compete in an open market.

Even if the above situation should prove to be the case, development of techniques directed toward the recovery of material from solid waste must continue to be explored. This is because motivation for solid waste recovery may be provided by the growing awareness and concern about the external diseconomies and social costs associated with the classical disposal-oriented methods of solid waste management. We are rapidly moving into a society in this country where, in areas such as pollution control, direct dollar costs are no longer the sole consideration. For example, the full costs of air pollution from burning refuse whether in dumps or in most modern incinerators have not yet been accurately measured. Similarly, the social costs of a landfill operation (which can be positive or negative) or of an incinerator operation cannot be readily determined. Still more important, perhaps, is consideration of external diseconomies such as resource depletion. Although some materials, such as cellulose, are converted by disposal-oriented practices to basic constituents (such as carbon dioxide and water) and thus enter a natural cycle culminating in the growth of timber, other materials, such as metals and their oxides, can be lost irretrievably to future generations through present solid waste disposal practices.

Battelle believes that all the "costs" of solid waste disposal, including the social as well as economic costs of pollution and considerations regarding resources management, must be evaluated before comprehensive decisions regarding recovery and reutilization of solid waste can be made. Thus, it is quite possible that landfill and conventional incineration (i.e., without by-product recovery) may become unattractive for solid waste management, not from the development of an economic (in the direct dollar cost sense) recovery process, but rather through increased dissatisfaction with associated undesirable side effects in the form of aesthetic offenses to the environment, resource depletion, and objectionable or harmful pollution of the land, air, and water resources.

Further evaluation of recovery and reuse of solid waste should include a systems analysis approach to the standard engineering costs potential of solid waste recovery. This approach would establish a priority of best, next best, etc., processes in a classical economic sense. One or more of the "best" processes (which may still prove to be uneconomical in the classical sense) could lead to a broader program, taking into account the less tangible costs associated with solid waste disposal in an attempt to justify recovery and reutilization of material.

Although it is not difficult to believe that social-cost considerations rather than classical economics will determine future directions in solid waste management, implementation of these considerations will be difficult. The major problem is the definition and measurement of the various social costs, once they have been identified. This is essential in order to provide decision criteria to municipal and other government officials who are committed, to a large extent, to least-cost alternatives (in terms of direct dollar expenses) in the disbursement of public funds. Consequently, it appears that significant technical and public relations effort is required, aimed at defining the magnitude and long-term effects of disposal-oriented solid waste management practices.

VIII. Potentially attractive process combinations

Based upon the data collected and the trends observed during this study, several potentially attractive process combinations have been conceived. Before the technical and economic merits of these possibilities can be evaluated, however, several kinds of additional information are required. One, of course, is the unit process cost and performance data that has been the main subject of this study. But it is also necessary to explore in some detail the immediate and long-range market potential in various sections of the country for salvage material and the several manufactured by-products which can, in principle, be produced in solid waste recovery systems. Because of differences in local economies, markets would be expected to vary from one region to another. It is also true that in a given locality, the market for any single product is not likely to be so great that a solid waste recovery system producing only one product would be economically attractive. This indicates that a multiple-product system would be desirable. However, as the number of product streams increases, the magnitude of each decreases and higher costs associated with small-scale processing are incurred. The volume of individual product streams can be increased by increasing the input to the plant, but this approach may cause increased waste collection costs since a greater area must be served by a given plant. Notwithstanding these considerations and the general lack of data upon which to base quantitative process evaluations, several potentially attractive process combinations have been developed and are outlined below. In accord with the conclusions outlined previously, a common feature of the proposed combinations is that they are all centered about by-product recovery with auxiliary salvage streams.

Four major recovery schemes can be identified—composting, conventional waste-heat recovery, pyrolysis, and hydrolysis followed by biochemical production of alcohols or protein. It is not surprising that three of the above four schemes (all except composting) are directed toward the utilization of the cellulosic fraction of solid waste, the largest single component in mixed municipal solid waste. In fact composting is also capable of recovering some cellulosic materials since a limited amount of paper and related materials are desirable in compost.

Of the systems judged to be most promising for solid waste processing, each is directed toward a specific major objective, but also includes auxiliary salvage operations. Their common salvage objectives include reclaiming of steel and tin, precipitation iron for use at copper mines, materials for the manufacture of structural shapes, and residual material that can be used for landfill.

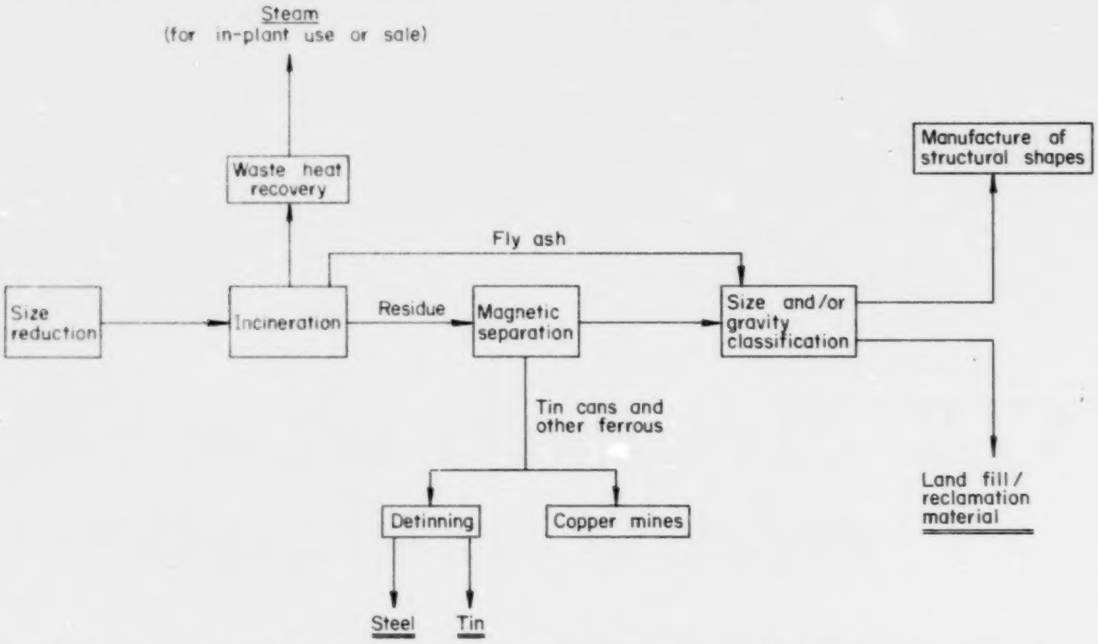
Steam
(for in-plant use or sale)
Waste heat recovery
Manufacture of structural shapes
Fly ash
Size reduction
Incineration
Residue
Magnetic separation
Size and/or gravity classification
Tin cans and other ferrous
Land fill / reclamation material
Detinning
Copper mines
Steel
Tin

FIGURE 77. *Solid waste processing system: waste-heat recovery and auxiliary salvage.*

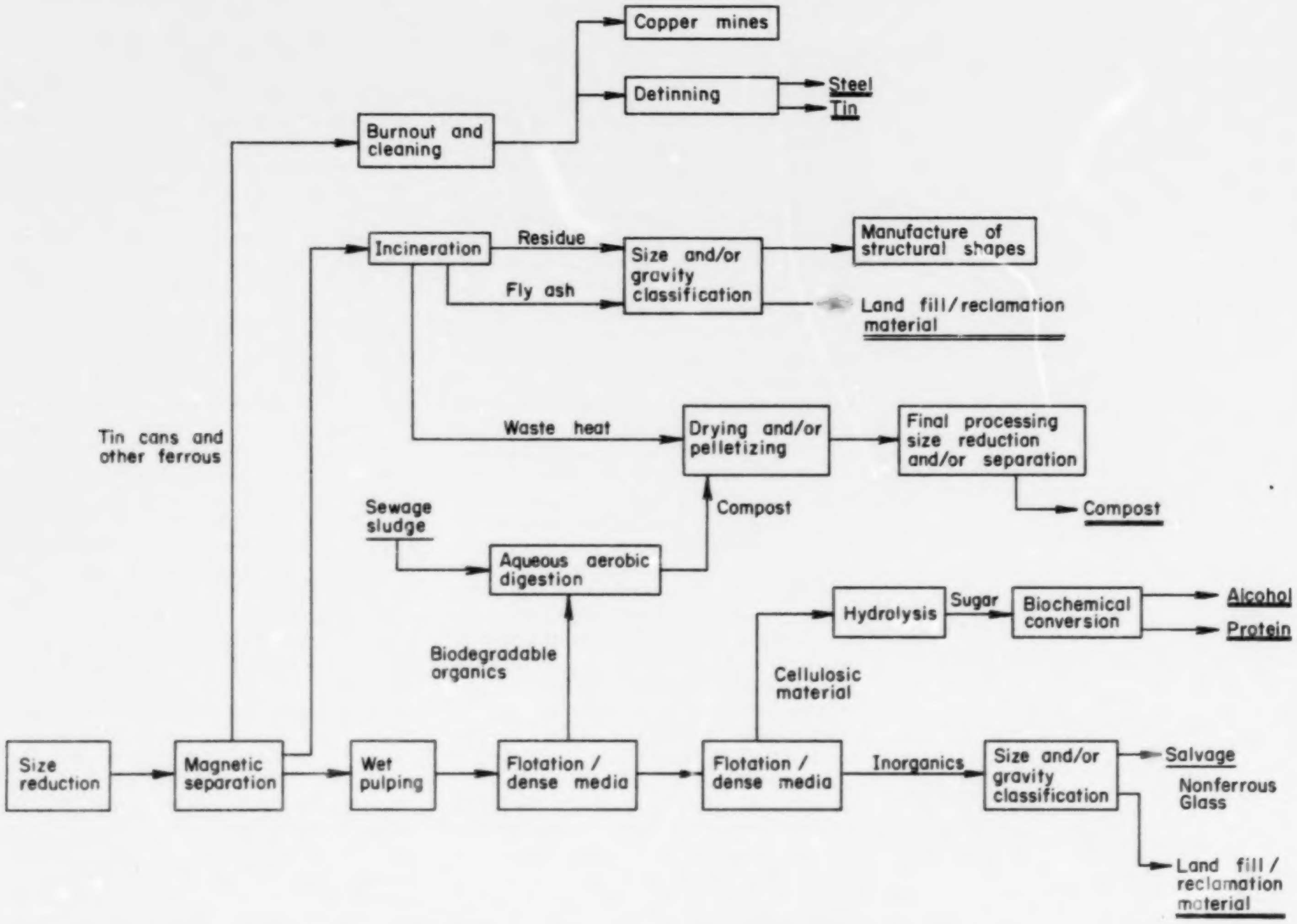
Copper mines
Detinning
Steel
Tin
Burnout and cleaning
Incineration
Residue
Size and/or gravity classification
Manufacture of structural shapes
Fly ash
Land fill/reclamation material
Tin cans and other ferrous
Waste heat
Drying and/or pelletizing
Final processing size reduction and/or separation
Compost
Sewage sludge
Compost
Aqueous aerobic digestion
Hydrolysis
Sugar
Biochemical conversion
Alcohol
Protein
Biodegradable organics
Cellulosic material
Size reduction
Magnetic separation
Wet pulping
Flotation / dense media
Flotation / dense media
Inorganics
Size and/or gravity classification
Salvage
Nonferrous
Glass
Land fill / reclamation material

FIGURE 78. *Solid waste processing system: biochemical conversion and auxiliary salvage.*

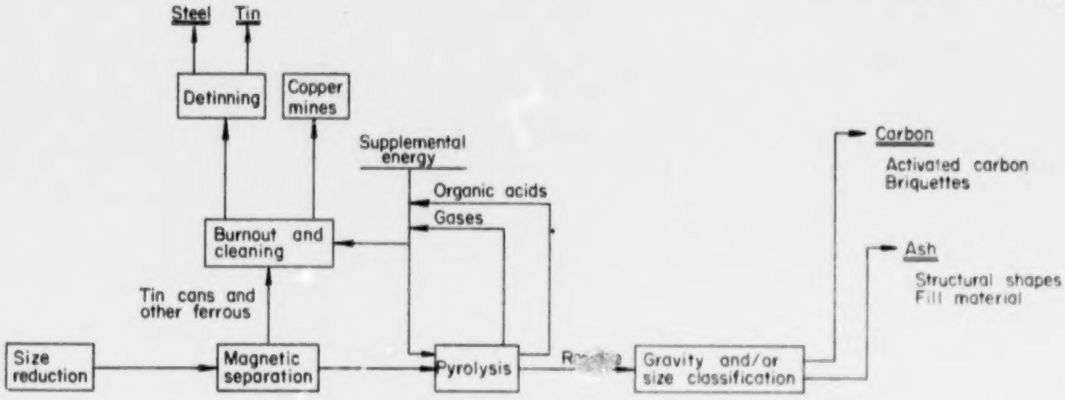
Steel
Tin
Detinning
Copper mines
Supplemental energy
Organic acids
Gases
Burnout and cleaning
Tin cans and other ferrous
Size reduction
Magnetic separation
Pyrolysis
Residue
Gravity and/or size classification
Carbon
Activated carbon
Briquettes
Ash
Structural shapes
Fill material

FIGURE 79. *Solid waste processing system: pyrolysis and auxiliary salvage.*

The major objectives of the system are: waste-heat recovery—steam (Figure 77); biochemical conversion—alcohol, protein (Figure 78); and pyrolysis—carbon (Figure 79). Conventional composting and waste-heat recovery were not outlined separately since each has been covered in detail in previous sections. Flow diagrams of the three schemes suggest that several minor variations related to equipment and unit-process permutations and combinations are possible. The merits of such combinations need to be evaluated in terms of total processing costs, which cannot be provided with the current state of knowledge, and local market opportunities for the various by-products and salvage materials. Selected elements of the proposed processes (Figures 77 to 79) could be combined to synthesize a processing system capable of producing a multitude of products.

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Appendix A
Summary of Contacts Established

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Tele-phone	Visit	Yes	No	Yes	No	Yes	No	Size reduc-tion	Sepa-ration	Recovery and utilization
Aerojet General Corporation Building 160, Dept. 3401 Azusa, California 91702	Mr. Robert Mitchell	X		X	X		X		X			X	X
Aerospace Commercial Corp. 2502 Ash Street Palo Alto, California 94306	Mr. Richard D. Smith, President	X	X		X		X		X				X
Allis Chalmers 846 S. 70th Street Milwaukee, Wisconsin 53201	Mr. A. J. Mestier, Manager Planning & New Products.	X			X			X		X	X	X	
Altoona FAM Company Altoona, Pennsylvania 16601	Mr. Carlos McCleave, Plant Supervisor.	X		X	X		X			X	X	X	X
American Can Company 100 Park Avenue New York, New York 10017	Mr. D. J. Lohuis	X			X			X		X		X	
American Public Health Association 1740 Broadway New York, New York 10019	Dr. George J. Kupchik, Director of Environmental Health.	X			X		X		X				X
American Design & Development Corporation. 200 Essex Street Whitman, Massachusetts 02382	Mr. A. Dean Tomlinson, Vice President.	X			X		X			X			X
American Pulverizer Company 1249 Macklind Avenue St. Louis, Missouri 63110	Mr. Don Graveman, Sales Manager	X			X		X		X		X		
Asplundh Chipper Company Chalfont, Pennsylvania 18914	Mr. Harold E. Gentile, Manager	X			X		X		X		X		
Atkins Saw Division, Nicholson File Company. 1825 North Theobold St. Greenville, Missouri 38701	Mr. M. M. Krebs, Jr.	X			X			X		X			
Baldwin Lima Hamilton Corp. Lima Division Lima, Ohio 45802	Mr. Robert Wheeler	X			X		X			X	X		
Barber-Greene Company 400 N. Highland Avenue Aurora, Illinois 60507	Mr. Carl H. Ulm, Sales Engineer	X			X		X		X		X		
Barnes Drill Company 818 Chestnut Rockford, Illinois 61102		X			X			X		X		X	
Bassichis Glass Company 2323 W. 3rd Street Cleveland, Ohio 44113	Mr. Erwin Stern	X	X	X	X		X		X			X	X
Bauer Brothers Company, The 1718 Sheridan Avenue Springfield, Ohio 45501	Mr. R. M. Ginaven, Ind. Division	X			X	X	X		X		X	X	
Black Clawson Company 606 Clark Street Middletown, Ohio 45042	Mr. Joe Baxter	X	X		X		X		X		X		
Blaw Knox Company Food & Chemical Equipment Division 1325 S. Cicero Chicago, Illinois 60660	Mr. Roscoe Warner	X			X					X	X		
Blaw Knox Company Food & Chemical Equipment Division 43 Winchester Avenue Buffalo, New York 14211		X				X						X	

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Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
Blower Application Company 7259 N. 51st Street Milwaukee, Wisconsin 53223		X			X		X		X		X		
Borg-Warner Company Mechanical Sales Division Vernon Avenue at Thomas Los Angeles, California		X				X						X	
Boxboard Research & Development Association. 350 S. Burdick Mall Kalamazoo, Michigan 49006	Mr. A. T. Luey, Manager	X			X		X			X			X
Branford Vibrator Company New Britian, Connecticut 06050	Mr. G. W. Cartier, General Manager	X			X		X			X		X	
BSP Corporation 6205 Harvard Avenue Cleveland, Ohio 44105	Mr. Paul J. Cardinal, Manager Sanitary Division.	X			X		X			X	X		
Buffalo Forge Company 495 Broadway Buffalo, New York 14240	Mr. Gunnar Hurtig, Jr., Export Manager.	X			X			X		X			
Buffalo Hammer Mill Company 1245 McKinley Parkway Buffalo, New York 14218	Mr. D. F. Ruff	X	X		X		X		X		X		
Buffalo Pattern Corporation 828 Hertel Avenue Buffalo, New York 14216		X				X						X	
Buhler Brothers (Canada) Ltd 1925 Leslie Street Don Mills, Ontario	Mr. E. Rimensberger	X			X		X		X		X		
Bux-Shrader Magnetic Products 11623 South Broadway Los Angeles, California 90061	Mr. K. L. Gille, General Manager	X			X		X		X			X	
Cameron-Yakima, Inc P.O. Box 1554 Yakima, Washington 98901	Mr. E. C. Cameron, President	X	X	X	X		X		X				X
Carter-Day Company 665 19th Avenue, N.E. Minneapolis, Minnesota 55418		X			X			X		X		X	
Centriblast Corporation Vista Industrial Park Campbells Run Road Pittsburgh, Pennsylvania 15205	Mr. Paul Daria, Vice President	X	X	X	X		X		X		X		
City of Atlanta Department of Public Works Atlanta, Georgia	Mr. S. W. Grayson, Director of Sanitation; Mr. Robert D. Speer.	X			X		X		X				X
City of Chesterfield Department of Public Cleansing Chesterfield, N.E. Derby, England	Mr. A. E. Higgison, Superintendent of Public Cleansing.	X			X		X			X			X
City of Cleveland Division of Engineering & Construction Department of Public Service Cleveland, Ohio	Mr. Herbert Wicks, Civil Engineer	X			X			X		X	X		
City of Madison City-County Building 210 Monona Avenue Madison, Wisconsin 53709	Mr. John Reinhardt, Project Director.	X	X	X	X		X		X		X		
City of Memphis Memphis Light, Gas, & Water Division P.O. Box 388 Memphis, Tennessee 38101	Mr. Steve Warren, Director of Public Relations.	X			X		X			X			X
City of Miami Department of Public Works 1950 N.W. 12th Avenue Miami, Florida 33136	Mr. J. Grady Phelps	X	X		X		X		X				X
City of Mobile City Hall 109 S. Royal Mobile, Alabama 36602	Mr. Lambert C. Mims, Public Works Commissioner; Mr. Meyers, Public Works Superintendent.	X		X	X		X		X		X		X
City of New York Department of Sanitation 125 Worth Street New York, New York 10013	Mr. Maurice Feldman, Acting Commissioner.		X	X	X		X			X	X		
City of San Diego Utilities Department 7100 Colorado Avenue La Mesa, California 92041	Mr. D. A. Hoffman	X			X		X		X				X
Combustion Engineering, Inc Raymond Division 427 Randolph Chicago, Illinois 60606		X				X						X	
Continental Can Company 633 Third Avenue New York, New York 10017		X				X						X	
Crobaugh Laboratories 3800 Perkins Avenue Cleveland, Ohio 44114	Mr. Henry R. Friedberg, Vice President.	X			X			X		X			X

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
D & J Press Company 605 Main Street Tonawanda, New York 14150		X			X		X			X			X
Dan B. Vincent, Inc 3015 Third Avenue Tampa, Florida 33605	Mr. Daniel B. Vincent, President	X			X		X			X		X	
Day & Zimmermann Associates 1700 Sansom Street Philadelphia, Pennsylvania 19103	Mr. W. D. Brown	X			X								X
Denver Equipment Company 1400 17th Street Denver, Colorado 80217	Mr. J. E. Carr, Central Sales Manager.	X	X	X	X		X		X	X	X	X	
Derrick Manufacturing Co 590 Duke Road Buffalo, New York 14225	Mr. H. Wm. Derrick, Jr., President	X			X		X			X		X	
Dings Machine Separator Co 4740 W. Electric Avenue Milwaukee, Wisconsin 53219		X			X		X			X		X	
District of Columbia Sanitation Department District Building 14th & E Streets Washington, D.C.	Mr. Robert Perry, Deputy Chief	X			X		X			X	X		X
Dorr-Oliver Company, Inc 77 Havemeyer Lane Stamford, Connecticut 06904	Mr. W. E. Budd, Director of Water Management Systems; Mr. Mike Lewis.	X	X		X		X	X		X	X	X	
Duplex Mill and Manufacturing Company. 400 Sigler Springfield, Ohio 45506		X			X		X			X		X	
Environmental Engineering, Inc 2324 S.W. 34th Street Gainsville, Florida 32601	Dr. Charles I. Harding, President	X	X	X	X		X					X	X
Entoleter, Inc P.O. Box 1919 251 Welton Street New Haven, Connecticut 06509	Mr. Franklin R. Farrow, Sales Application Engineer.	X			X		X			X	X		
Eriez Manufacturing Co Asburg Road at Airport Erie, Pennsylvania	Mr. Robert F. Merwin, President; Mr. Frederick D. Buggie, Manager Technical Contracts Systems.	X	X	X	X		X		X			X	
Esco Corporation 2141 N.W. 25th Street Portland, Oregon 97210	Mr. Max Gowing	X			X		X			X			
Exebec Corporation P.O. Box 4175 Bridgeport, Connecticut 06607		X				X							
Exolon Company [illegible]50 East Niagara Tonawanda, New York 14150	Mr. R. R. Harty, President	X			X			X		X		X	
Fairfield Engineering Co Marion, Ohio 58466	Mr. John Houser, Director of Research; Mr. James Coulson, Sales Manager.	X	X	X	X		X		X				X
Farrel Corporation 148 Maple Street Ansonia, Connecticut 06401	Mr. A. H. Trerorrow, Jr.	X			X		X			X	X		
Fate Roote Heath Company 607 Bell Street Plymouth, Ohio 44865		X				X							
S. G. Frantz Company, Inc 60 E. Darrah Lane Trenton, New Jersey 08638		X				X						X	
French Oil Mill Machinery Company 1088 Green Street Piqua, Ohio 45356	Mr. John L. Dillon	X	X		X		X		X		X		
Fuller Company 124 Bridge Street Catasauqua, Pennsylvania 18032		X				X							
Fuller Company Infilco Division P.O. Box 5033 Tucson, Arizona 85703	Mr. E. J. Roll	X			X			X		X		X	
Gainesville Municipal Waste Conversion Authority. P.O. Box 1152 Gainesville, Florida 32601	Mr. H. W. Houston		X	X	X		X		X		X	X	X
Garden State Paper Company River Road Garfield, New Jersey 07026	Mr. Frank Lorey, Corporate Research Director.		X	X	X		X			X		X	X
General Products of Ohio West Bucyrus Street Crestline, Ohio 44827	Mr. Herbert T. Cobey, President	X			X		X			X	X		
Glasgow University Department of Mechanical Engineering. Glasgow University Glasgow, Scotland	Dr. Andrew Porteous, Lecturer in Mechanical Engineering.	X			X		X		X				X

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
Glass Container Manufacturers Institute, Inc. 1625 K Street, NW. Washington, D.C. 20006	Mr. John H. Abrahams, Manager of Environmental Pollution Control Programs	X		X	X		X			X		X	X
Glenn King Company Houston, Texas.	Mr. Michael Gummond		X		X			X		X		X	
Westinghouse Air Brake Goodman Division 4634 S. Halsted Street Chicago, Illinois 60609	Mr. Carl E. Hanson, Sales Manager	X			X		X			X	X		
Gruendler Crusher & Pulverizer 2900 N. Market Street St. Louis, Missouri 63103	Mr. Wm. P. Gruendler, President	X			X		X		X		X	X	X
Gundlach, T. J., Machine Company Division of JMJ Industries, Inc. P.O. Box 385 Belleville, Illinois 62220	Mr. J. D. Frazer, Sales Engineer	X			X		X		X		X		
Hammermills, Inc 625 C Avenue Cedar Rapids, Iowa 52405	Mr. Wm. D. Robinson, Manager of Solid Waste Systems.	X	X		X		X		X		X		
azemag U.S.A., Inc 60 E. 42nd Street New York, New York 10017	Richard E. Kleinhaus, Vice President	X	X		X		X		X		X		
Heil Company, The 3000 W. Montana Street Milwaukee, Wisconsin 53201	Mr. Arnold F. Meyer	X	X	X	X		X		X		X		
Ir. J. A. Hendricks Oud Loosdr Dyk 239 Oud Loosdrecht, The Netherlands		X				X						X	
C. B. Hobbs Company Milpitas, California 95035	Mr. Ronald Guard, Plant Superintendent.			X	X		X	X					X
Hoffman Industries P.O. Box 214 Syracuse, New York	Mr. James J. Joseph, Field Engineer	X			X			X		X		X	
Hugo Neu-Proler 901 New Dock Street Terminal Island, California 90731	Mr. Richard Neu, General Manager		X	X	X			X		X	X	X	X
Hutchinson Manufacturing Company P.O. Box 9335 Houston, Texas 77011	Mr. W. C. Philipp, Manager of Industrial Development.	X			X		X			X		X	
Indiana General Corp 6001 S. General Avenue Cudahy, Wisconsin 53110	Mr. W. A. Bronkala, Sales Manager	X			X		X			X		X	
International Disposal Corp 2801 22nd Street St. Petersburg, Florida 33712	Mr. Roger Lynn, Plant Manager; Mr. Frank Rigo, Maintenance Superintendent.			X	X		X		X		X	X	X
Ionics Corporation 65 Grove Street Watertown, Massachusetts 02172													
Iowa Manufacturing Company 916 16th Street, N.E. Cedar Rapids, Iowa 52402	Mr. Kenneth Lindsay, Sales Manager	X			X		X			X	X		
Jeffrey Manufacturing Co 956 N. 4th Street Columbus, Ohio 43201		X				X							
J. H. Day Company 4900 Beech Street Cincinnati, Ohio 45212		X				X						X	
Kennametal, Inc 700 Lloyd Avenue Latrobe, Pennsylvania 15650	Mr. Gail P. McCleary, Project Engineer.	X			X		X			X			
Kennedy Van Saun Corp 405 Park Avenue New York, New York 10022	Mr. Lester R. Ferguson, Vice President.	X			X		X			X	X		
Lawden Manufacturing Company, Ltd Spring Road Ettingshall, Wolverhamptom, England	Mr. A. S. Pittwood, Managing Director.	X			X		X			X			X
Link Belt Company 138 E. Court Street Cincinnati, Ohio 45202							X			X			
Link Belt Company Department TR-67 Prudential Plaza Chicago, Illinois		X				X						X	
Lippman Products Operations Hewitt Robins Division Litton Industries 666 Glenbrook Road Stamford, Connecticut 06906		X				X					X		
Lippman Products 4603 W. Mitchell Milwaukee, Wisconsin 53214		X				X						X	
Logemann Brothers Company 3150 W. Burleigh Street Milwaukee, Wisconsin 53245	Mr. R. J. Smiltneek, Director	X	X		X		X		X		X		

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
Lone Star Organics Corp. 9225 Lawndale Avenue Houston, Texas 77012	Mr. Gerald Vaughn, Plant Manager; Mr. Wages, Assistant Plant Manager.	X	X	X	X		X		X		X	X	X
Los Angeles By-Products Company 1810 E. 25th Street Los Angeles, California 90058	Mr. C. C. Sexton, President; Mr. Ben Litchfield, Manager Sacramento Division.	X	X	X	X		X			X	X	X	X
Los Angeles County Sanitation District 2020 Beverly Boulevard Los Angeles, California 90057	Mr. Walter E. Garrison, Chief Engineer; Mr. Frank Dair, Division Engineer.	X		X	X		X			X			X
Luria Brothers 5650 Boyle Avenue Vernon, California 90058	Mr. Mort Seiden, Manager; Mr. Andrew DeVries, Operating Engineer.		X	X	X		X			X	X		X
Luria Brothers Five Points Road Cleveland, Ohio	Mr. William Magnes, Director of Research; Mr. Curtis Dudda, Plant Manager.		X	X	X		X			X	X	X	X
Machinery and Equipment Company 514 Bryant San Francisco, California 94107		X				X						X	
Manufacturers Equipment Co 218 Madeira Avenue Dayton, Ohio 45404		X			X			X		X	X		
Metropolitan Washington Council of Government. 1250 Connecticut Ave., N.W. Washington, D.C. 20036	Mr. John J. Lentz	X			X		X			X			X
Metropolitan Waste Conversion Corporation. P.O. Box 1026 Wheaton, Illinois 60187	Mr. Victor Brown, President; Mr. I. Anderson, Manager, Plant Engineering Dept.	X	X	X	X		X		X		X	X	X
Franklin P. Miller & Son, Inc 36 Meadow Street E. Orange, New Jersey 07017	Mr. Harold Galanty	X			X		X			X	X		
Mitts & Merrill 109 McKoskry Street Saginaw, Michigan 48601	Mr. J. W. Ranous, Sales Manager; Mr. Goddard.	X			X		X			X	X		
Munson 210 Seward Avenue Utica, New York 13503	Albert D. Matthai, Jr.	X			X		X			X	X		
McLanahan Corporation 200 Wall Street Hollidaysburg, Pennsylvania 16648	Michael W. McLanahan, Assistant Sales Manager.	X			X		X		X		X		
McNally Pittsburg Manufacturing Company. Drawer D Pittsburg, Kansas 66762	Mr. R. F. Wesner, President	X			X		X			X	X		
NV Vuilafvoer Maatschappij (VAM) Jacob Obrechstraat 67 Amsterdam-Z, The Netherlands	Dr. Ir. Stolp, Director	X			X							X	
National Canners Assn 1950 6th Street Berkeley, California 94710	Mr. Walter Rose, Head of Water and Waste Engineering Section.	X	X	X	X		X			X		X	
National Committee for Paper Stock Conservation. The Chase Bldg. 212 N. Kingshighway St. Louis, Missouri 63108	Mr. Wm. M. Russell, Special Consultant.	X		X	X		X			X		X	X
National Engineering Company 549 W. Washington Blvd. Chicago, Illinois 60606	Mr. A. J. Dumcius, Sales Manager	X			X			X		X		X	
National Organic Corporation 904 First Federal Building Atlanta, Georgia 30303	Mr. Stanley Spiegel	X			X			X		X			X
National Waste Conversion Systems Corporation. 425 East 51st Street New York, New York 10022	Mr. Stephen Varro	X				X							X
Naval Facilities Engineering Command. Atlantic Division Norfolk, Virginia	Mr. R. E. Short, LCDR, CEL, USN Acquisition Coordination Officer.	X			X		X						X
New York State Health Dept Office of Local Governments Albany, New York													
Newaygo Engineering Co Newaygo, Michigan 49337	Mr. Ray Sweitzer, Sales Manager	X				X					X		
Newell Manufacturing Co 726 Probandt Street San Antonio, Texas 78204	Mr. Scott Newell, Vice President		X		X		X		X		X		
New York University West 177th Street and Cedar Avenue Bronx, New York 10453	Dr. Elmer K. Kaiser	X			X		X		X			X	
Nordburg Manufacturing Co Box 383 Milwaukee, Wisconsin 53201		X				X					X		
Noro Industrial Corporation S. Cottage Grove Avenue Chicago, Illinois		X				X						X	

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
Ohio Magnetics 142-A East Pearl Avenue Lima, Ohio 45801		X				X						X	
W. W. Oliver Manufacturing Company 10 Beard Avenue Buffalo, New York 14214		X				X					X		
Oregon State University Agricultural Engineering Department Corvallis, Oregon 97330	Dr. Virgil H. Freed; Mr. Robert R. Groner.	X			X		X		X				X
Orville Simpson Company 1230 Knowlton Street Cincinnati, Ohio 45223	Mr. Norman L. Zundt, Sales Engineer.	X			X			X		X		X	
Pan American Resources, Inc. 5443 San Fernando Rd., W. Los Angeles, California 90039	Mr. Robert Buckbinder, Vice President; Mr. Charles Fink, Marketing Manager.	X	X	X	X		X		X				X
Pennsylvania Crushers P.O. Box 100 Broomall, Pennsylvania 19008	Mr. D. F. Webb, Sales Engineer	X			X		X		X		X		
Prater Industrial Products Inc 1515 S. 55th Street Chicago, Illinois 60650	Mr. P. E. McKamy, Vice President	X			X		X			X	X		
Arthur G. McKee & Company Process Machinery Div. 650 5th Street San Francisco, California 94107	Mr. J. J. Davey	X			X		X			X	X		
Proler Steel Corporation 7501 Wallisville Road Houston, Texas 77020	Mr. Samuel Proler, President; Mr. Herman Proler, Executive Vice President.	X	X	X	X		X			X	X	X	
PHS-TVA Compost Plant RFD 4 Johnson City, Tennessee 37601	Mr. John Wiley, Research Director; Dr. Carl Sova, Microbiologist.		X	X	X		X		X		X	X	
Quad-City Solid Waste Room 53—City Hall Patterson, New Jersey	Mr. W. T. Ingram	X			X			X		X		X	
Raymond G. Osborne Laboratories 2636 S. Grand Avenue Los Angeles, California 90007	Mr. Phillip S. Osborne, Vice President.	X		X	X		X			X			
Reed Paper Group, Ltd Aylesford Paper Mills Lakefield Maidstone, Kent England	Mr. James Peddie, Project Engineer	X											
Rensselaer Polytechnic Institute Department of Civil Engineering Troy, New York	Dr. Wm. A. Shuster	X				X							
Rietz Manufacturing Co 182 Rodd Road Santa Rosa, California 95402	Mr. Warren S. Enochian	X			X			X		X	X		
A. J. Sackett & Sons Co 1702 S. Highland Ave. Baltimore, Maryland 21224	Mr. Walter Sackett, Jr., Vice President.	X			X		X			X	X		
San Diego State University School of Engineering San Diego, California	Dr. R. A. Fitz	X	X		X		X		X				X
Segredyne Corporation 23 Charles Street Cambridge, Massachusetts 02141		X			X			X		X		X	
Slick Industrial Company Pulverizing Machinery 100 Chatham Road Summit, New Jersey 45103	Mr. Dennis Reekers, Representative.	X			X		X			X	X		
Smith Engineering Works 532 E. Capital Drive Milwaukee, Wisconsin 53201	Mr. J R. Smith, Vice President	X			X		X			X	X		
John R. Snell Engineers, Inc. 221 N. Cedar Street Lansing, Michigan 48933	Dr. John R. Snell, President	X			X			X		X			
Sortex Company of North America P.O. Box 160 Lowell, Michigan 49331	Mr. T. G. Gilbert, Vice President	X			X		X		X			X	
Sprout Waldron & Company, Inc. Muncy, Pennsylvania 17756	Mr. Howard D. Egli, Jr.	X			X		X	X		X	X	X	
Stanford Research Institute 820 Mission Street South Pasadena, California 91108	Mr. R. A. Boettcher, Research Engineer.	X			X			X		X		X	
Stedman Foundry & Machine Company, Inc. Aurora, Indiana 47001	Mr. Ronald L. Bradford, Factory Sales Engineer.	X			X		X			X	X		
J. C. Steele & Sons P.O. Box 951 Statesville, North Carolina 28677	Mr. J. C. Steele, Jr.	X			X		X			X	X		
Stephens-Adamson Manufacturing Company. 19 Ridgeway Avenue Aurora, Illinois 60507	Mr. R. H. Humm, Vice President	X			X			X		X			

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
Strong Scott Manufacturing Company Minneapolis, Minnesota 5541?	Mr. George H. Paulson	X			X			X					
Sturdevant Mill Company Park & Clayton Streets Dorchester, Boston, Massachusetts 0 2122	Mr. A. T. Glynn, Engineer	X			X		X		X		X		
Sumitomo Shojo Chicago, Inc. 208 S. La Salle Street Chicago, Illinois	Mr. N. Murakami	X			X		X			X			X
Sundstrand Corporation Sundstrand Machine Tool Division 2531 11th Street Rockford, Illinois 61101	Mr. Mario Calvagna, Chief Proposal Engineer.	X			X			X		X		X	
Sutton, Steele, and Steele, Inc. 1029 S. Haskell Dallas, Texas 75223	Mr. Rodgers Hill	X	X		X		X		X			X	
SWECO 6111 E. Bandini Blvd. Los Angeles, California 90022	Dr. Albert M. Soldale, Vice President	X		X	X		X			X		X	
Syntron Company Homer City, Pennsylvania 15748	Mr. L. R. Morgan, Advertising Manager.	X		X	X		X		X			X	
TAPPI 360 Lexington Avenue New York, New York 11216	Mr. H. O. Teeple	X			X		X			X		X	X
Tennessee Valley Authority F202 National Fertilizer Development Center. Muscle Shoals, Alabama	Mr. Earl E. Elliott, Chief, Fertilizer Distribution & Marketing Staff.	X			X			X		X			X
Testing Machines, Inc. 72 Jerico Turnpike Mineola, Long Island, New York 11501		X				X					X		
Tezuka-Kosan Company, Ltd 7-Chome, Ojima Tokyo, Japan	N. Murakami	X			X		X			X			X
Thomas Foundries, Inc. P.O. Box 1111 3800 Tenth Avenue N. Birmingham, Alabama 35234		X				X					X		
John Thompson, Ltd. Taristock House East Weburn Walk Taristock Square London W.C.I., England		X				X							
Tollemache Composting Systems, Ltd. 25 Berkeley Square London W.I., England	Mr. D. H. G. Tollemache	X			X		X		X	X	X	X	
W. S. Tyler Company 8200 Tyler Boulevard Mentor, Ohio 44060	Mr. S. J. Janovac, Application Engineer.	X			X		X			X		X	
Union Carbide Paper Chemicals 270 Park Avenue New York, New York 10017		X			X		X			X		X	
United Compost Service 3701 Kirby Drive Houston, Texas 77006	Mr. Jeffrey George, President	X	X	X	X		X			X	X		X
United Conveyor Corp. 6505 N. Ridge Blvd. Chicago, Illinois 60626		X			X			X		X			
Universal Road Machinery Company Emrick Street Kingston, New York 12401		X			X		X			X	X		
Universal Vibrating Screen Company P.O. Box 942 Racine, Wisconsin 53405		X				X						X	
University of California Sanitary Engineering Research Laboratory 1301 E 46th Street Berkeley, California	Dr. Clarence J. Golueke, Research Biologist.	X		X	X		X		X				X
University of California Davis Campus Agricultural Engineering Department Davis, California	Dr. Samuel A. Hart	X	X	X	X		X		X				X
University of Florida Gainesville, Florida 32601	Mr. Dennis Falgorit			X	X		X		X				X
University of Hartford Department of Mechanical Engineering Hartford, Connecticut	Mr. Alfred Eggen	X	X		X		X		X				X
University of Louisville Department of Civil Engineering Louisville, Kentucky	Mr. J. E. Heer	X			X		X		X			X	X

Company/organization	Contact(s)	Information furnished											
		Vehicle			Response rec'd		General		Technical data		Technical area		
		Letter	Telephone	Visit	Yes	No	Yes	No	Yes	No	Size reduction	Separation	Recovery and utilization
U.S. Bureau of Mines Metallurgy Research Center College Park, Maryland	Mr. Carl Rampacek, Research Director; Mr. Paul Sullivan, Supervisor, Chemical Engineer.	X	X	X	X		X		X			X	X
U.S. Bureau of Mines Washington, D.C.	Mr. Frank Cservenyak, Manager, Solid Waste Projects.	X			X		X			X			X
U.S. Industries, Inc., Engineering Ltd. Burtonwood Warrington, Lancashire England		X										X	
U.S. Naval Station Department of Public Works Norfolk, Virginia 23511	ENS Ralph Hesler, CEC, USN		X										X
USPHS-TVA Compost Plant Johnson City, Tennessee 37601	Dr. John S. Wiley Research Director	X	X	X	X		X		X		X	X	X
U.S. Plywood Champion Papers, Inc 777 Third Avenue New York, New York 10017		X				X							X
Virginia Polytechnic Institute College of Agriculture Blacksburg, Virginia	Mr. D. C. Martins, Assistant Professor.	X			X			X		X			X
Vortec Products 1414 W. 190th Street Torrence, California 90504		X				X						X	
West Virginia University School of Mines Morgantown, West Virginia 26505	Mr. Harry E. Shafer, Jr., Supervising Research Technologist.	X			X		X		X				X
WEMCO Division of Arthur G. McKee P.O. Box 15619 Sacramento, California 95813	Mr. D. W. Jenkinson, Consulting Engineer.	X			X		X			X		X	
Williams Patent Crusher & Pulverizer Company. 807 Montgomery St. Louis, Missouri 63102	Mr. J. H. Herb, Regional Sales Manager.	X			X		X			X	X		
Wascon Systems, Inc Hatboro, Pennsylvania 19040	Mr. James, Sattelle Marketing Assistant.	X		X	X		X			X	X		
Wheelabrator Corporation 454 S. Byrkit Mishawaka, Indiana 46544	Mr. Robert L. Orth	X			X			X		X		X	
Ir. W. A. G. Westrate Stationkade 70 Amsterdam-Z The Netherlands		X			X			X		X		X	

Appendix B

New Size-Reduction Equipment Designs

PATENT ART

The patents that were selected (from a review of U.S. patents collected by the Bureau of Solid Waste Management, Solid Waste Information Retrieval System[1]) for study by Battelle were the ones more closely related to solid waste size reduction. Most of these were improvement patents on standard size-reduction equipment. The following patents were selected because they disclose elements showing promise for future application to municipal solid waste size reduction.

Patent Number 2,248,108—Bottle Breaking Machine

The gravity-actuated member disclosed may have use in a preliminary operation on municipal solid waste. Automatic action of hammers on municipal solid waste as it is conveyed could be in the nature of a series of shattering blows. These blows could be continuous or be initiated by a bulky item in a manner similar to electric typewriter action.

Patent Number 2,641,165—Multiple Disk, Radial Axis Wet Pulper

The multiple abrasive disks shown may have some advantage over the single disk in a wet pulper, with, perhaps, added action if the axis were canted to allow disks to overlap and promote the formation of a slurry toroid.

Patent Number 2,708,552—Refuse Cutting Machine

The lump-breaker, feather-compacter feeder disclosed is similar to crushing-type feeders used on some hammermills and suggests a possible modification to "homogenize" bagged garbage.

Patent Number 2,738,932—Preliminary Disintegrating Machine

The meshing stationary blades (called breaker anvils in the patent) and breaker arms (helically inclined members) have action similar to impact crushers with shredder teeth and added axial conveying action. On selected material, such as municipal solid waste with bulky items excluded, a machine such as this might be useful in an automatic preliminary operation.

Patent Number 2,980,345—Ultrasonic Apparatus and Method of Comminution

The ultrasonic siren used appears to be best suited to friable materials; a heterogeneous mixture such as municipal solid waste would attenuate the energy severely. The absence of moving parts in contact with the material, however, would minimize wear and allow free passage of material. This would appear to be useful in a system using automatic presorting.

Patent Numbers 3,188,942 and 3,191,872

These are wet pulpers with screw-type extrusion dewatering devices. Screening of unpulpable material is also disclosed. The separation of materials found in municipal solid waste is partially successful, but the need for a conveyor-type, self-cleaning screen for automatic sorting is indicated.

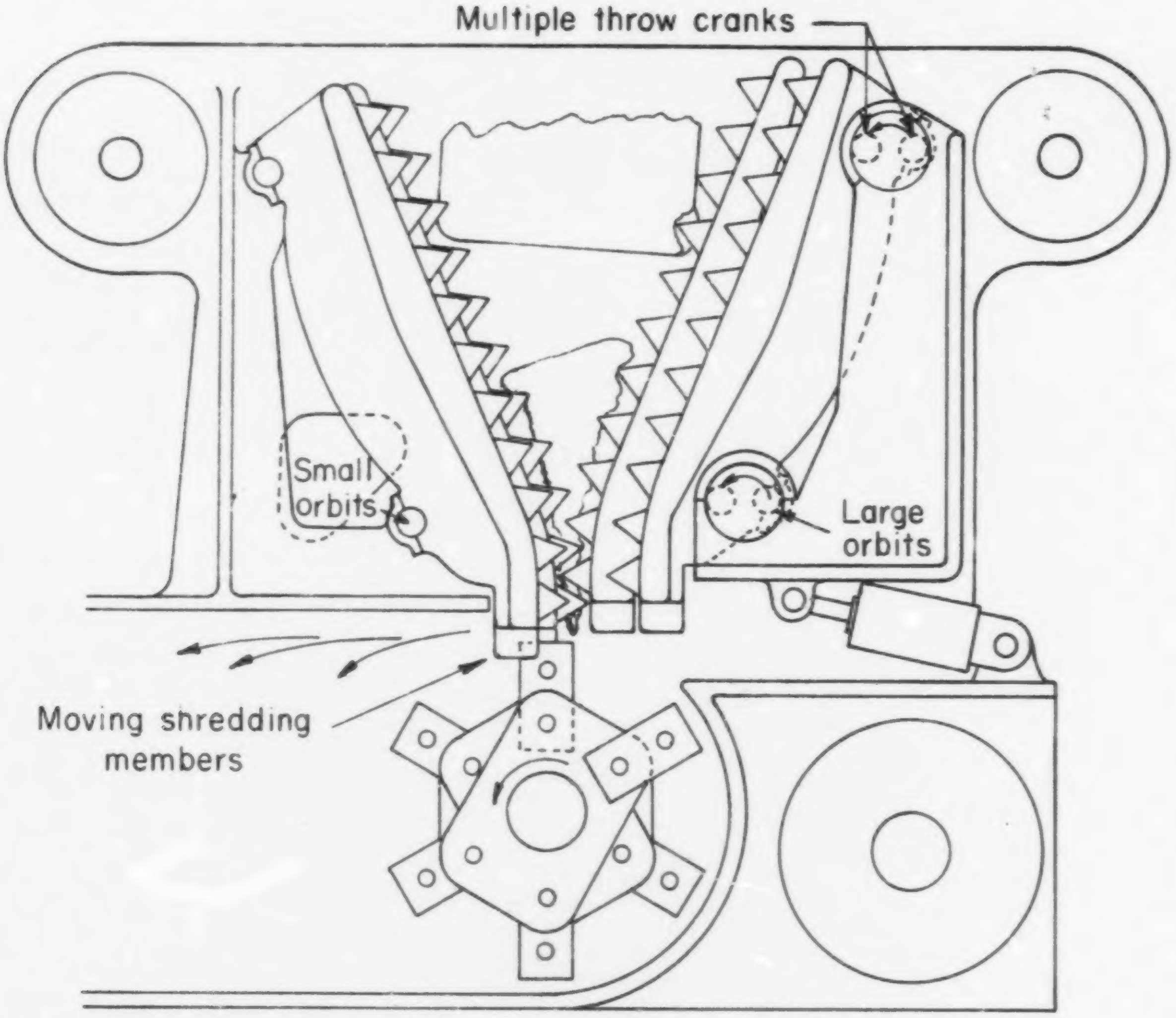

FIGURE B–1. *Improved hammer and hammer-mounting means for hammermill.*

BATTELLE'S CONCEPTS OF IMPROVEMENTS

In the course of the solid waste size-reduction studies, improvements for machine components and in machine combinations became apparent.

Improvements for Machine Components

Hammermill hammers, hammermill feeders, and moving shredder members were considered candidates for improvements in their components.

Hammermill Hammers. Prevalent uneven hammer wear and long downtime for hammer change or resurfacing indicate the need for improved hammers and means for faster hammer changing.

Threaded pivots to permit quick removal or rotation of individual hammermill hammers and a hammer designed to improve efficiency are conceived (Figure B–1). This arrangement also staggers the hammers to minimize the number of simultaneous blows, thus reducing vibration and noise. A rake angle, b_1, will promote a piercing action and reduce wedging of the material between the hammers and the grate bars. Wear area to a given radius, r, is also increased as shown by comparing a_1 on the hammer with rake angle b_1 and a_2 on the square hammer with a negative rake angle b_2. The center of percussion is also nearer the hammer tip on this design, which would reduce the ratio of weight-to-impact.

Hammermill Feeders. The feed waste into hammermills was observed to be a critical operation. Even when fairly selective material is handled, where such bulky items as oil drums and refrigerators have been preseparated, operations near rated capacity require close control to prevent overloading. Automatic conveyor speed control based on hammermill power demand has been used, but rather large power input excursions due to nonuniform material and slow system response were observed. This wide swing in power input dictates a somewhat conservative average power setting and indicates the need for improved hammermill feeding.

Homogenizing feeds has been con-

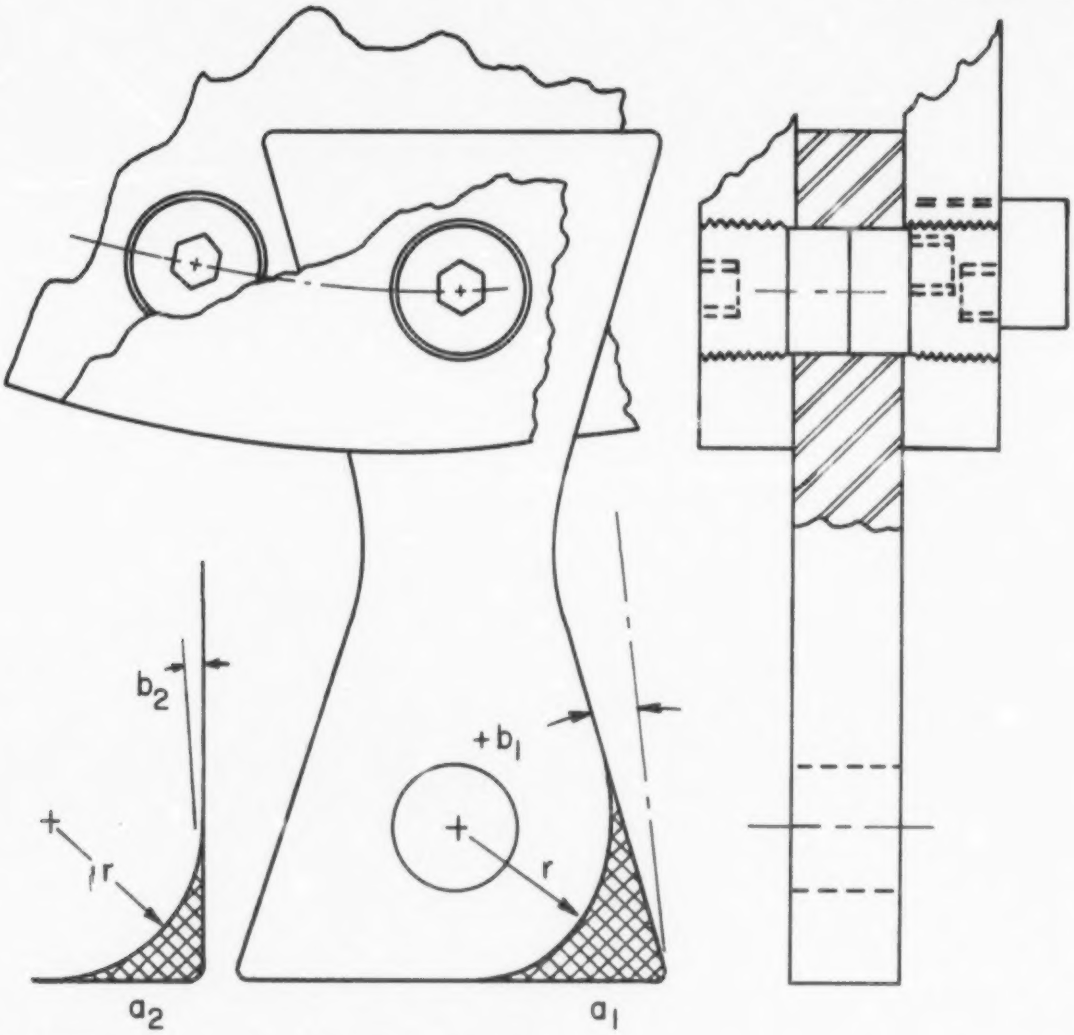

FIGURE B–2. *Improved hammermill feeder.*

sidered, ranging from the wiping action of a gate in a conveyor system to a crushing-tearing concept (Figure B–2). This type could be in the form of a hopper to accommodate surges in input and variations in feed rate. Automatic speed control could be performed with minimum backlash by monitoring the crushing and tearing action to produce uniform semimacerated ribbons. The feeding and tearing would be done by the piercing and pulling action of hard teeth on converging walking beams driven in a variety of orbits by multiple-throw cranks.

Moving Shredder Members. Some of the hammermills studied utilize shredding members which mesh with the hammers to provide additional tearing action. Product size can be determined by the clearance of the hammers and the shredding members. Free recirculation in the hammermill is prevented in these, and jamming and buildup on stationary shredding members may occur. One set of the walking-beam members could be used as moving shredding members (Figure B–2). In operation, buildup of material on the shredding members would be periodically released by the retracting action.

Combination Improvements

Combinations of existing size-reduction equipment offer some advantages when applied to solid waste. Among these are the combined shearing and hammermilling and combined crushing and hammermilling, which prompted the composite configuration (Figure B–2). In this concept, close clearance of passing teeth could also be provided for a shearing action. Conceivably, a combination such as this could accommodate an extremely wide range of unsorted materials.

Combinations of hammermills and wet pulpers were also studied, and it is indicated that a primary size reduction may use more horsepower than the final size reduction. This could also be the case with a crushing and tearing feeding unit combined with the hammermill. Either of these combinations appears to promote synergistic effects.

Appendix C

Other Separation Patent Art

In addition to the separation technology discussed in preceding sections, other potentially applicable techniques have been extracted from the review of U.S. patents collected by the Bureau of Solid Waste Management, Solid Waste Information Retrieval System.[107] The information summarized below has been abstracted from the respective patents. Information is not available regarding current applications.

Patent No. 2,422,203—Specific Gravity Separation of Solids in Liquid Suspension—(June 17, 1947)

The invention relates to the recovery of solids from liquids by sink-float methods. Separation according to size or specific gravity is claimed. The invention claims an arrangement whereby the requirement to employ heavy media is eliminated. Specifically, a controlled centrifugal movement of a body of mixed solids in a liquid is claimed to permit clean and distinct separation between solids of different sizes and/or specific gravities in an aqueous pulp. The process was developed as an improved ore-beneficiation technique, although potential uses in coal-washery applications and the treatment of potash ores are claimed. Performance data on ores in the size range 6–200 mesh are provided. Performance attainable on various forms of solid waste cannot be established without experimental studies, except that it should be noted that potential applications are limited to relatively fine fractions.

Patent No. 2,474,695—Collecting and Separating Apparatus—(June 28, 1949)

This device was designed to separate particles from a fluid medium, to separate heavier fluids from lighter ores, and to remove dust, sand particles, and chips from castings and other items produced in foundries, mills, etc. A mixed fluid stream is accelerated in a duct connected to an elbow or bend. As the stream enters the elbow, heavier materials are separated from lighter ones because of differential centrifugal forces. A complex baffle arrangement is provided in the elbow to collect the separated material streams. No data indicating performance of the device are provided in the patent.

Patent No. 2,561,665—Continuous Classifier for Solids—(July 24, 1951)

This device was developed as an improved technique for separating solids of various specific gravities from a fluid medium, provided that all solids to be separated have a specific gravity greater than the fluid. A series of tanks are provided such that the cross-sectional area of flow path increases, tank-by-tank, in the direction of flow. A liquid suspension is introduced in a tank in a downward and upward path thereby inducing the settling of solids in each tank. Because the flow path of each subsequent tank is of larger cross-sectional area, the upward velocity of flow decreases, thus permitting the deposition of lighter solids in each stage. An adjustable baffle is provided in each tank which is claimed as a novel means for controlling flow and minimizing turbulence.

Patent No. 2,689,646—Fluid Flotation Separator and Method for Separating Pulverized Materials—(September 21, 1954)

This device relates to a method for separating fines from pulverized ma-

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terials using gas flotation. Problems with previous state-of-the-art are reported to be (1) difficulty in dislodging and rendering buoyant an efficient quantity of fines, which are distributed throughout the pulverized material; and (2) a tendency of fines to agglomerate and form heavy nodules which are not rendered buoyant and consequently not separated.

The new method involves conveying a pulverized material over an inclined porous surface at an appreciable speed. A stream of gas under pressure is passed through the porous surface from below and then through the pulverized material. As the pulverized material is conveyed over the porous surface, small portions of the moving material are agitated by the gas to break down the nodules. Simultaneously, small portions of the material adjacent to the upper surface of the material stream are elevated above the material and thereafter are permitted to fall in a cascading effect through the flotation gas flowing upwardly from the surface of the material stream. The fine particles of material in the cascading portion are rendered buoyant and become entrained in the flotation gas. The agitation and elevation of the pulverized material are produced by several deflector members positioned above the porous plate. After the flotation gas and the fine particles of material entrained therein have been conducted to a collector, the velocity of the flotation gas is reduced to permit the fine particles of material to settle and be collected.

Patent No. 2,689,648—Separation of Metallic from Nonmetallic Particles—(September 21, 1954)

This invention provides a method for separating metallic from nonmetallic particles. The method is based on the phenomena that nonmetallic particles may become electrostatically charged and thereby caused to react to forces created by an electrostatic field. The mixture to be separated is transported along a horizontal plane by means of a conveyor through an electrostatic field of alternating potential. Alternating forces created by this field impart sufficient vibration to the nonmetallic particles resulting in a stratification and concentration of metallic particles which do not so respond. Separation of the resultant layers of the two types of particles is accomplished mechanically. This device is an extension of long-established minerals-beneficiation technology whereby stratification and concentration of ores is accomplished by vibratory means alone. Performance data and feed requirements are not outlined in the patent, although it is expected that small particle size and low moisture content would be essential. Potential applications to solid waste recovery are judged to be minimal and would probably be limited to the removal of nonferrous metals from other nonmetallic components. The cleaning of compost may be one such potential application.

Patent No. 2,707,554—Grain Separators—(May 3, 1955)

This invention is claimed to be an improved machine for the removal of weed seeds from cereal grains (wheat, oats, barley, rye, etc.). The device is also claimed to segregate various grains from one another. The device provides a three-stage separation employing in combination a variable transverse diameter-dividing assembly, a weight-dividing (specific gravity) assembly, and a selective length-dividing assembly operating on a given mass of grain in the order listed above. Width separation is accomplished by one or more cylindrical screens with adjustable circumferential longitudinal openings which permit the division of the mixture into two fractions according to transverse diameter. Density separation is accomplished by classification in an air separator. Length separation is accomplished by means of a complex arrangement of rotating disks, the operation of which is difficult to describe in narrative form.

Patent No. 2,806,600—Separator for Separating Granular Poultry Feed from Poultry Bedding—(September 17, 1957)

This device is a very simple application of screening and consists essentially of a perforated cylinder mounted to rotate about a horizontal axis. Immediately below the cylindrical screen in a semicircular trough. A means is provided to deliver feed contaminated with bedding material to the rotating and tumbling screen; for collecting, in the trough, clean feed passing through the screen; and for collecting and discharging from the screen the bedding material separated from the mixture.

Patent No. 2,820,705—Method of Recovering Metals from Nonferrous Metallurgical Slags—(January 21, 1958)

Generally stated, the process is designed for recovering metals from nonferrous metallurgical slags containing reducible compounds of the metals and involves establishing a reduction zone in a furnace containing a matrix of carbon or other reducing materials for the reducible compounds. This zone is maintained at a temperature between the melting point of the slag and 1450 C. Also, an atmosphere of carbon monoxide and carbon dioxide is established in such proportions that log CO/Co_2 is, broadly, from -4 to $+2$.

The molten slag is contacted with the reducing material in the reduction zone by percolating it downwardly. This requires but a few seconds. However, during this short time under the conditions present in the reduction zone, the reducible compounds of the valuable metals to be recovered are converted to the free metals, while the iron content of the slag is substantially unaffected.

Accordingly, there is produced a treated slag product which contains the valuable metals in the reduced or free state. The treated slag containing these metals is then withdrawn from the reduction zone almost immediately, to prevent reduction of any iron compounds which might be present and concomitant contamination of the desired metal products. The treated slag then may be processed for separation of the metal fraction from the residual slag.

Potential applications in solid waste processing would relate to the recovery of high-temperature incinerator slags.

Patent No. 2,868,376—Heavy Media Separator—(January 13, 1959)

This device is an adaptation or modification of a spiral classifier. In general, classifiers of this type consist of a tank having an inclined bottom, an overflow for fines or "float," an elevated discharge for the "sink" or coarse rake products, and a spiral conveyor for agitating the pulp and raking the sink out of the tank. Three classifiers are used to separate a mass of grains of mixed sizes and/or different specific gravities into various grades or sizes.

This patent claims a modification of the spiral classifier to utilize heavy media, which in turn permits the segregation of mineral ores into a sink fraction, a middling fraction, and a float fraction. This device appears to be very similar to units manufactured by Denver Equipment Company and discussed in an earlier section of this report.

Patent No. 2,986,277—Method and Means for Treating and Sorting Comminuted Substances—(May 30, 1961)

The invention relates to an apparatus for sorting comminuted particles on the basis of density, by means of a whirling motion. However, unlike a cyclone where particles move concurrently with air flow, this invention provides for a portion of the particles to move counter to the flowing gases.

The device is adaptable to particle size ranges on the order of 50 microns, and so would have extremely limited application for solid waste recovery.

Patent No. 3,064,806—Apparatus for Wet Sizing of Solid Materials—(November 20, 1962)

This invention relates to a means for wet sizing of finely ground (35–200 mesh) solid particles. The process combines hydraulic classification and wet screening and is claimed to be superior to either technique used alone. The invention consists of a stationary container equipped with an impeller to impart rotary motion to the mixed slurry, which is fed constantly to the unit; an inclined screen; and means for directing the upper portion of the slurry against the screen. Coarser materials are retained in the container and are removed after settling. Finer particles passing the screen are collected along with the overflow as a separate product. Because of the small particle sizes, direct application to solid waste processing will probably be extremely limited.

Patent No. 3,127,016—Sorting of Articles—(March 31, 1964)

This device employs the mechanics of partially elastic collision to effect separation. Particles or articles to be sorted are impinged one by one onto a stationary target element of desired elastic properties. Elastic properties of the colliding materials determine the amount of energy transfer and, hence the subsequent movement of the impinged particle. Provision is made to sort the particles into two fractions, depending on whether or not the resulting trajectory deflects the particles a certain degree.

Patent No. 3,327,857—Object Counting and Discrimnating Device—(June 27, 1967)

This device is designed to automatically sort broken tablets from whole tablets, although extension of the principles involved to other applications is possible. A method is provided for comparing by photometric means every tablet to be sorted with a standard, i.e., integral tablet. Tablets which are smaller than the standard, because of being broken or other defects, are rejected. Those which compare favorably to the standard are retained. It is claimed that, with modification, the basic invention may be constructed to distinguish shape, color, or other physical characteristics. Operating principles are very similar to the Sortex optical separator discussed in a previous section.

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